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Increasing the Collaboration on Thermal Energy Storage Systems at SolarPACES TCP

Current Activities in the TES Working Group

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Abstract. This paper presents, mainly, the just recently launched collaboration topics in the Thermal Energy Storage Working Group (TES WG) of the SolarPACES task III. The collaboration topics can be grouped into four focus areas one dealing with the main issues related to molten salt loops, like for example, with the reliability of equipment and instrumentation used in this type of hydraulic loops; another in relation to TES tanks issues, like for example, the identification of failures at high temperature and solutions to implement in the tank design; another focussed on corrosion issues of structural materials used in molten salt loops and on how different coatings can be used for that, and finally another topic focussed on the used of TES not only by storing energy of a CST plant but of other non-dispatchable renewables, like PV or wind, in a Carnot battery.

Keywords: Thermal Energy Storage, SolarPACES, International Collaboration

1. Introduction

SolarPACES Technological Collaboration Programe , TCP, has the mission to facilitate technology development, market deployment and energy partnerships for sustainable, reliable, efficient and cost-competitive concentrating solar technologies. Thanks to reliable thermal storage systems, this technology has the great advantage of being dispatchable on demand. Since 2015, a working group focused on Thermal Storage has been functioning under the SolarPACES umbrella, within Task III, Solar Technology and Advanced Applications. This working group (WG) is formed by independent experts from worldwide research centers and companies, providing expertise and know-how according to their field of expertise and confidentiality limitations. This unparalleled framework joined experts to, for example, define an appropriate procedure for measuring accurately the heat capacity of solar salt with nanoparticles by DSC, [1], or, in conjunction with the SFERA-III EU project, to share experience in reliability of components and instrumentation used in molten solar salt loops, [2], and in agreeing on the

KPI that characterize a thermal storage prototype and on the method to obtain such values experimentally [3].

Apart from the updating of the database containing information of R&D activities in thermal storage developed carried out by the participants, and which can be found in [4], four new topics have been launched along 2024:

1. Carnot Batteries
2. TES Tank Issues
3. Structural Materials: Corrosion and Coatings
4. Molten Salt Technology

This paper presents the activities these topics will cover and their main contributors.

2. Carnot Batteries

Energy storage is crucial for renewable energy integration as it mitigates the intermittency of renewable sources like solar and wind, ensuring a stable and reliable power supply. By storing excess energy generated during peak production times, energy storage systems enable continuous energy availability, support grid stability, and facilitate a broader adoption of renewable energy technologies. Among the different energy storage technologies, Carnot Batteries feature several advantages as its equipment is based on established technologies, their geographic location independence, and their limited environmental impact as they do not rely on rare or toxic materials.

The integration of Carnot Batteries with Concentrated Solar Power (CSP) plants appears particularly interesting as the two technologies share the same technologies for the hot thermal energy storage (TES) and power cycle. Furthermore, the coupling of Carnot Battery technology with CSP could significantly increase the utilization of the power cycle and TES during the months characterized by the lowest solar radiation and improve the plant economic profitability by offering grid storage capability on the electricity market. Finally, as Carnot Batteries have the ability to also store cold energy, they allow the power cycle to reject heat at lower temperatures, leading to an increase in efficiency and a more resilient operation to ambient temperature variations.

Despite all of these advantages, Carnot Batteries technology still face several barriers to commercial deployment, mainly related to the lack of incentives and clear policy regulations, as well as the need to demonstrate and validate the technology through pilot plants and prototypes. In this context, a new topic of the SolarPACES Thermal Storage working group has been launched with the aim of bringing together experts from the industry and academia, to investigate the potential role of Carnot Batteries integrated in CSP systems and support their development. The main actors involved in this task are CEA (France), CENER (Spain), China Solar Thermal Alliance (China), Chinese Academy of Sciences (China), CIEMAT (Spain), CSIC (Spain), CYD (Spain), DLR (Germany), ENEA (Italy), NREL (U.S.A.), Politecnico di Milano (Italy), University of Évora (Portugal), University of Salamanca (Spain), University of Sevilla (Spain), and others. The mentioned objectives will be pursued by carrying out five different activities:

- *In-depth Literature Review and Technology Assessment*: this activity involves thoroughly reviewing existing literature on Carnot Batteries for CSP applications, identifying key system components, and classifying alternative and emerging technological solutions. The goal is to define the main Key Performance Indicators (KPIs) and to identify the most critical challenges and opportunities in the technology's development.
- *Market Analysis, Regulatory and Policy Framework, and Stakeholder Engagement*: by reviewing the current and future market landscape and identifying potential services and benefits that CSP-based Carnot Batteries can provide, this activity aims to engage

relevant stakeholders. This will help share expertise and experiences from ongoing or upcoming projects, thereby identifying opportunities, threats, and key players in the industry.
- *Modeling and Simulation*: this activity involves reviewing and comparing different numerical models and tools, creating a database of assumptions and constraints used in these simulations, and ensuring consistency and accuracy through coherence checks and cross-validation. Expected outcomes will include identifying best practices and emerging trends in simulation methodologies and refining existing models to enhance their accuracy and reliability.
- *Technical Feasibility Study*: by collecting and reviewing data from literature and stakeholders, the working group aims to create a comprehensive database of case studies. These case studies will be used to assess the application envelope and feasibility of integrating Carnot Batteries with CSP systems, highlighting the technical advantages and potential benefits compared to alternative solutions.
- *Knowledge Sharing and Dissemination:* the organization of workshops, webinars, and technical sessions will provide platforms for sharing findings, exchanging best practices, and fostering dialogue within the scientific community. Furthermore, the publication of the main findings in white papers and technical reports will help establish the SolarPACES Thermal Storage WG as communication leaders in this field and promote potential collaborations and partnerships with other researchers and institutions.

All these activities aim to build a solid foundation for strategic planning among stakeholders, while fostering a collaborative network of research institutions and industrial players. Moreover, the provided insights will be fundamental for components manufacturers and system integrators in making decisions regarding product development, market entry strategies, and investment priorities.

3. TES Tanks Issues

According to statistics from the China Solar Thermal Alliance (CSTA), the global installed capacity of CSP plants has amounted to 7,550 MW by the end of 2023. Molten salt thermal energy storage (TES) has emerged as the mainstream thermal storage technology for the existing commercial CSP plants. For a 50 MW central receiver CSP plant, the TES system is mainly constituted by a giant cold tank and a giant hot tank with an effective volume of approximately 20,000 cubic meters. The operating temperature of the hot molten salt tank reaches 565 °C, or even higher. During operation, the cycle of thermal charging and thermal discharging causes the molten salt inventory to change frequently and the temperature to vary from approximately 420℃ to 565 ℃ in the hot tank. Under these operational conditions, thermal fatigue, creep, buckling, and weld defects are all potential factors that lead to stress relaxation cracking and eventually result in leakage failures of the molten salt tanks. It still remains a challenge to ensure that the molten salt tanks remain in service in excess of 25 years.

In recent years, leakage failures have occurred in the tanks, resulting in substantial economic losses for commercial power plants. Therefore,reliable operation is essential for the future of CSP technologies, and it is urgent to address the failures and propose technological solutions for molten salt TES tanks. In this context, the SolarPACES TES work group has established a series of activities related to the topic of TES tanks. The participants engaged are institutions and companies from several countries, including BBCMC (China), CENER (Spain), CGN (China), CIEMAT (Spain), Colorado School of Mines (USA), DLR (Germany), IEECAS (China), INTA (Spain), NREL (USA), NWEPDI (China), University of Barcelona (Spain), University of Birmingham (UK), University of Évora (Portugal), and others. Through their contributions, the following four activities will be implemented to advance the technologies of TES tanks.

- *Identification of tank failures and development of corresponding technological solutions:* This activity involves investigating the tank failures that occurred in central receiver plants, exploring the special technologies of tanks that have been maintaining normal operations, and identifying the key components/zones susceptible to leakage failure. The goal is to address the tank failures and propose effective technological solutions.
- *Guidelines for molten salt storage tanks*: Aiming to lay the foundation for the establishment of guidelines applicable to molten salt TES tanks used in CSP plants, this activity focuses on five tasks including material statistics of storage tanks and auxiliary parts, structural design and load analysis of key components, exploration of key technologies for fabrication and erection, investigation of methods for inspecting the welding joints, and identification of operational conditions and maintenance requirements.
- *Methods of lifetime prediction:* The objective of this activity is to propose a method for evaluating the comprehensive fatigue lifetime of the molten salt storage tanks. For that, it will be necessary to review the fatigue lifetime prediction theory of classical pressure vessels and the welding fatigue lifetime prediction theory, lifetime prediction modeling and numerical simulation, experimental validation approaches of the lifetime prediction model and simulation methodology, and analysis of the effect of molten salt corrosion on the tank's lifetime.
- *Monitoring system and method to ensure safe operation*: The primary objective of this activity is to identify potential leakage failure by continuously monitoring the operational status of storage tanks.This activity includes design and optimization of the measuring point arrangement through analyzing the various possibilities of leakage failures; enhancement of the existing monitoring system by intelligently measuring temperature, inventory level, displacement of foundation and leakage, exploration of the measurement instruments and methods for local stress and thermal expansion of the tank wall and floor.

In conclusion, with the implementation of all these activities, the expected outcomes include proposing the technological solutions for leakage failures, establishing the initial framework of guidelines applicable to molten salt TES tanks, formulating a lifetime evaluation system for high-temperature tanks, and strengthening the monitoring measures to ensure safe operation. Furthermore, a collaborative network among worldwide research institutions and industrial sectors is expected to be constructed. Their profound knowledge and rich experiences will drive the innovation and technological advancement of molten salt TES tanks by sharing academic findings and exchanging engineering practices.

4. Structural materials and coatings

One of the main challenges on TES systems at high temperature are in relation to material corrosion issues, being one of the key parameters to control since it is the most common failure cause of the components. Also, the conditions in this industry are such that particularly localized type of corrosion attack is often favoured; occurring in small local areas, and being difficult to detect before leaks or damage of the component already occurs. For example, deposits often form to cover the initiated corrosion pits thus hiding them visually, and conventional non-destructive test methods for wall thickness measurements are not well suited to detect localized thickness losses. Additionally, in renewable energy industry, the prevention of high temperature corrosive attacks plays a critical role in aspects such as reliability, quality, safety and profitability. In this task, different corrosion issues related with CSP plant operation will be studied, including standardization of the corrosion evaluation techniques, control of impurities, proposal of coatings and design of new alloys to be tested in commercial CSP plants. Some of the institutions involved in this task, leaded by University of the Basque Country (Spain) and University of Barcelona (Spain), are CIC Energigune (Spain), DLR (Germany), NREL (U.S.A.), ENEA (Italy), CIEMAT (Spain) and others. The research activities are divided in 4 activities:

- *Corrosion evaluation guidelines for molten salts in CSP plants*: A standardization of the testing parameters involved in corrosion evaluation will be carried out, including flow rates for dynamic testing (including autoclave or pilot plant tests), impurities acceptance level and welding behaviour in commercial alloys.
- *Selection of promising alloys to be applied as structural materials in high-temperature molten salts*: A review of the most promising alloys for high temperature molten salts, including Ni-base, alumina forming austenitic (AFA) alloys, high entropy alloys (HEA) in contact with carbonate and chloride molten salts will be developed, including LCA and LCC assessment of the systems.
- *Revision of corrosion evaluation techniques and procedures*: Review and standardization of the corrosion evaluation techniques applied to high temperature molten salts, comparing gravimetric and electrochemical techniques and thermophysical characterisation of molten salts during corrosion processes.
- *Material coating composition and deposition techniques*: In this section, a comprehensive review of the materials tested as coatings in CSP plants will be developed as well as the proper deposition techniques available and the boundary working conditions required at each structural zone in the CSP plant.

The expected outcomes include a review and update of the corrosion evaluation guidelines already published, including recommended flow rates in tanks, HXs, or central receivers, level of impurities accepted, alloys used as structural materials and other evaluations developed by the participants and renowned in the literature and to establish an international guidelines/standard sponsored by IEA SolarPACES, specifically on molten salt corrosion guidelines.

Finally, a specific strategy in the development of coatings will be studied, including the proposal of protective barriers and deposition techniques in order to reduce and improve the current production costs.

5. Molten Salts Technology

The combination of heat storage systems and advanced materials enhances the overall performance and reliability of CSP plants, contributing to their significant potential in providing renewable energy solutions. Nevertheless, it is worth mentioning that molten nitrate salts, including the (60 wt. % NaNO3, 40 wt. %KNO3), have a restricted upper temperature limit due to the occurrence of thermal decomposition at temperatures exceeding 600°C. This limits the thermal storage capacity and the efficiency of the power plant. One international initiative to overcome this limitation is the Generation 3 Concentrating Solar Power Systems (Gen3 CSP) programme, initiated by the US Department of Energy (DOE) in 2018. The programme's main objective is to address risks associated with next-generation CSP technology by integrating advanced thermal energy storage (TES) systems and implementing the CO2 Brayton power cycle at temperatures up to 800°C. Nonetheless, one of the selected pathways focuses on overcoming the key technical challenges arising from the interaction between molten salts and structural materials under high-temperature conditions, because higher storage and operating temperatures cause challenges related to higher corrosion rates and cycle stability. In this context, an ambitious WG on Molten salts technologies that aims to address the comprehensive development of novel molten salts and materials technologies for novel CSP thermal energy storage systems, enabling operation at temperatures surpassing the current 600ºC, and increasing plant dispatchability. A holistic approach is considered to achieve higher efficiencies in the thermal storage of the CSP plants: new sustainable molten salts with improved physicochemical characteristics and optimum resistance properties, that will allow near-zero corrosion rate operational conditions, and the possibility to reach 850ºC in the absorber surface of the receiver. Moreover, in the actual CSP plants, so far, no corrosion sensor systems have been applied to monitor thermal storage plants systems. This situation limits the corrosion behaviour monitoring of the materials, even in the actual molten nitrate's thermal storage CSP plants, up to reaching a catastrophic corrosion failure. Thus, it is required to monitor this corrosion, and to develop these systems, which jointly with materials/coating systems could allow to work under near-zero corrosion rate conditions. On another hand, ensuring long-term durability and minimizing maintenance costs are crucial considerations. Scaling up receiver systems for large-scale plants while maintaining cost efficiency requires careful attention to manufacturing costs and techniques. Accurate performance validation and modeling are vital for optimizing design and reducing costs. Ongoing research and development efforts focus on selecting cost-effective materials, improving thermal efficiency, ensuring system durability, optimizing manufacturing processes, and refining performance modeling.

Life cycle analysis will be analyzed in-depth, to include the environmental impact of the different molten salts systems, jointly with the structural materials and coatings WP. Partners from EU, USA and Canada, among others are in the expression of interest to work actively in this WG. These main activities will be developed in the WG:

- *Review of current and past CSP/TES/HTF projects related with molten salts*. This activity includes a Excell List and web pages for non-confidential results. Access of past and current CSP molten salt projects; a review of the last 5 years publications with a bibliometric analysis and identification of Key areas and a review of patents.
- *New molten salts formulations.* This activity aims to develop new salts, for basically thermal storage systems for CSP power plants. The following is threfore, required: Review of the state of the art for molten salts in TES, identification of possible interesting design new formulations. NDA required and characterization of the new molten salts systems and corrosion test for compatibility of Materials.
- *(Continuation of) testing of components in solar salt*, including compilation of previous results for components, identifying research/study gaps.
- *Predictive maintenance – corrosion monitoring.* The main objective of this activity is to promote and explore predictive maintenance in CSP plants in the TS-Molten salts, in order to connect corrosion sensors with predictive maintenance tools. Current state of the art in sensing and data mining analysis and organization of the installation in molten salts loops of sensors to monitoring the corrosion rate in molten salts under quasi-static and dynamic conditions are expected.
- *LCA analysis of new molten salts and components/new components.* Application of LCA – Life cycle analysis to perform under ISO 14040 & 14044 standards to analyze the environmental impact assessment of new formulations of salts and new components.
- *Energy assessment*, which includes *modelling the energy efficiency, heat transfer, LCOE, etc.*
- *Dissemination, Knowledge Transfer and Training Schools*. The main activities foreseen *here* are: the organization of workshops, webinars to exchange results and to enhance networking and common proposal, the publication of SolarPACES Technical group Reports, and the organization of Young Scientist SolarPACES Training Schools.

Author contributions

Esther **Rojas**: Conceptualization, Writing – original draft, Writing – review & editing. Rocío **Bayón**, Writing – review & editing. Darío **Alfani**: Writing – original draft. Chuncheng **Zang**: Writing – original draft. Camila **Barreneche**: Writing – original draft. Ángel **G. Fernández**: Writing – original draft. Francisco J. **Pérez Trujillo**: Writing – original draft.

Competing interests

The authors declare that they have no competing interests.

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