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Solar Facilities for the European Research Area

Reporting

Project Information

SFERA

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Final Report Summary - SFERA (Solar Facilities for the European Research Area)

Executive Summary:
Concentrated solar energy is a very promising renewable source of energy. Solar resource in the Mediterranean countries of the EU and in North Africa is huge. The best known application so far is bulk electricity generation through thermodynamic cycles, but other applications have also been demonstrated, such as production of hydrogen and solar fuels, water treatment and research in advanced materials.

Europe is a leader in research and development of this technology. Most of the large R&D infrastructures are European and our industry is leading the way in its commercial deployment, now in proposal. Five of them, CIEMAT-PSA, DLR, CNRS-PROMES, ETHZ and PSI were already part of a virtual laboratory consortium known as SolLAB (Alliance of European Laboratories for Research and Technology on Solar Concentrating Systems), which has initiated several networking activities since its creation in 2004. ENEA and WEIZMANN join the SFERA consortium, thus looking to consolidate a partnership as the reference European Solar Research Laboratory.

The activities carried out during the execution of SFERA project are:

- Networking: It has been created a stable Framework for co-operation in which resources are shared, common standards developed, duplication of research effort is avoided and interaction with European research, education and industry is encouraged.
- Transnational access: Doors of the most relevant R&D infrastructures has been opened to interested users, optimizing the use of the facilities and creating critical mass for new research initiatives.
- Joint Research: It has been achieved the development of common standards and procedures for better consortium performance and development of advanced instrumentation and new RI thus improving the services offered to the user community.

Project Context and Objectives:

Context

To achieve a secure and sustainable energy supply, and in view of growing climate change concerns, the EU has taken on the role of Kyoto protocol promoter and set out ambitious goals to achieve a large share of renewable energy in the European market.

The challenging European policy goals for non-nuclear energy are for the renewable energy contribution to triple up to 20% of primary energy by 2020.

Concentrated solar energy is a very promising renewable source of energy. The best known application so far is bulk electricity generation through thermodynamic cycles, but other applications have also been demonstrated, such as production of hydrogen and solar fuels, water treatment and research in advanced materials.

Europe is a leader in research and development of this technology. Most of the large R&D infrastructures are European and our industry is leading the way in its commercial deployment, now in proposal. Five of them, CIEMAT-PSA, DLR, PROMES-CNRS, ETHZ and PSI-STL were already part of a virtual laboratory consortium known as “SolLAB Alliance”, which has initiated several networking activities since its creation in 2004. ENEA and WEIZMANN now join the SFERA consortium, thus looking to consolidate a partnership as the reference European Solar Research Laboratory.

Objectives

In view of this challenge for research, development and application of concentrating solar systems involving a growing number of European industries and utilities in global business opportunities, the purpose of this project has been the integration, coordination and further focus scientific collaboration among the leading European research institutions in solar concentrating systems that are the partners of this project and offer European research and industry access to the best-qualified research and test infrastructures.

Through co-ordinated integration of their complementary strengths, efforts and resources, progress has been made more effective by:

Increasing the scientific and technological knowledge based in the field of concentrating solar systems in

both depth and breadth.
Providing and improving the research tools best-suited for the scientific and technologic community in this field.
Increasing general awareness and especially of the scientific community in the possible applications of concentrated solar energy, including creation of new synergies with other scientific disciplines (e.g. materials treatment, chemistry, physics, etc.).
The overall goal of these efforts have been creating a unified virtual European Laboratory for Concentrating Solar Systems, easily accessible to interested researchers, and thus serving as the structural nucleus for growing demand in this field in the developing European Research Area.
Such a European Solar Lab could also contribute to a sustainable secure European energy supply and to affirm basis for global competitiveness of European technology suppliers in this field, with strong prospects of growing worldwide markets in the coming decades.
The development of solar energy, in particular using concentrating systems, has a European dimension that requires a strong alliance of European research teams in order to enhance their research efficiency and technology development (Ref. Ares (2011)1343026 - 12/12/2011).
Project Results:
Expert working groups and round tables
The objectives were to establish working groups for experts and round tables to facilitate:
- The development of CSP standards for qualification of CSP components and plants
- The development and publication of specifications and/or standards in a standardization approach driven by demand
- The initiation of process for development of an European CSP Standard
- The dissemination of standardization activities and new CSP standard
For this purpose, experts of Sfera participants joined in three working groups between 2009 and 2011 to analyse the current state of technological specifications for standard development and certification procedures and define and coordinate further technical development. The status, gaps and further work programme has been identified.
A document on standardization activities has been developed in regards to the approach SFERA should have on CSP standardization. Already existing initiatives on this have already started and the first step was to analyze where SFERA was supposed to be positioned in regards to international initiatives. The analysis has been really useful by explaining how standardization is organized on the International, European and national levels, with focus on solar applications in general and on concentrated solar power. This has put awareness on all the participants that standards were urgently needed for CSP. This has also put forward the need for collaborations between the partners to actively be involved in other international standardization activities.

Exchange of personnel for harmonization of procedures
'Exchange of Best Practices for Harmonization of Working Methodologies' aimed at creating a more efficient consortium performance. It focuses more specifically on strengthening relationships within the consortium, thus creating a culture of co-operation, through short stays of personnel in others' labs. It is an attempt to get workers to acquire a global philosophy and attitude with respect to the whole set of SFERA infrastructures.
For this objective, exchange of personnel was planned between the partners in order to share know-how, participate in common R&D activities and to promote common technical and management methods. These

activities are crucial to carry on unified/coherent CSP activities and improve the services to the users at the different facilities.
During the course of the project, there has been the mobility of three personnel:
- One personnel from CIEMAT hosted by DLR – 3 months
Topic: The conceptual design of a high temperature molten salt test loop
- One personnel from CIEMAt hosted by ENEA – 1 week
Topic: Acquiring experience on experimental work on thermal storage system (TES) with integrated steam generator
- One final year PhD student from CIEMAT hosted by DLR – 3 months
Topic: Developing of a numerical model capable to describe the flow and heat transfer in graded ceramic foams, foreseen to be used as a receiver in a solar furnace to generate high temperatures for process heat applications.

Improve quality of testing services at R&D infrastructures for CSP
Standardized evaluation of the performance of CSP plants: one more step toward standardized testings

Within WP12 in JRA, partners have delivered two technical references to help the on-going standardisation European and international efforts towards rules for performance evaluation of CSP facilities. Such rules will be required for a mature market where a plant buyer and his investors must be sure of the performance of the product delivered by the plant designer.
The first report is a catalogue with definitions of the main parameters required for CSP components evaluation: SFERA deliverable D12.1.
The second report describes specific issues or methods for each technology and covers 15 measurement techniques to actually conduct CSP performance testing. This 131 pages long report will help any CSP new operator to evaluate the actual performance of a trough, a tower, a dish or a solar furnace, from the solar collection to the thermal conversion loop to produce electricity or chemical solar fuels. This report is titled “Proposal for a standard procedure titles “Guidelines for testing of CSP components”: SFERA deliverable D12.4.

Improved estimation of the concentrated solar power of CSP facilities: greater accuracy and better consistency

Users of the concentrating solar facilities require having an accurate and extensive knowledge of the energy distribution of the concentrated solar energy: this is gathered as solar flux characterisation. The choice of the best process to exploit this energy technically depends on this flux characterisation.
Different techniques exist to characterise the concentrated solar flux: direct methods with local sensors, indirect methods using calibrated camera and lambertian targets, computer based methods such as ray tracing techniques. All these techniques have strengths and weaknesses that make them collectively suitable for any technology or measurement objective. However, the consistency of the measures between techniques must be guaranteed: SFERA project has contributed to this objective thanks to the upgrade or the development of measurement systems and to their inter-comparison (see figure 1). Further steps will be conducted with the next flux intercomps planned in SFERA II project. Current work state has been presented at the conference SolarPaces 2013 and can be found in the SFERA deliverables D12.8 and

D12.13.

Figure 1. Concentrated solar flux measurements improvements: SFERA allowed the upgrade or the development of flux sensors and their acquisition system (calorimeters, heat flux sensors, cameras…) and allowed a flux inter-comparison campaign at the MWSF Odeillo.

Temperature measurements methods: one novel idea and several performance upgrades

Measuring the surface temperature of components under concentrated solar radiation is a tricky topic that requires dedicated equipment and dedicated methods.
A new method has been proposed, named double modulation technique, which addresses issues for both solar simulators and solar plants. Initial testing has been made and it will be the subject of a whole work package in SFERA II for further developing and testing this method. In addition, existing equipment have been upgraded and further tested, such as IR cameras and pyrometers. Details on these activities and on surface optical characterisation can be found in reviewed publications notably [Alxneit, I. (2011) Measuring temperatures in a high concentration solar simulator – Demonstration of the principle. Solar Energy, 85(3), 516–522] and SFERA deliverables D12.5 D12.7 D12.11 and D12.12.

Better knowledge of solar simulators: better extrapolation of R&D results to CSP plants

High flux solar simulators are versatile facilities for R&D of new solar processes. An excellent knowledge of their characteristics is required in order to exploit their capacity and extrapolate the performance of the tested processes to future industrial solar plants. WP12 within JRA has notably contributed in this field by allowing the characterisation and the improved control of the PSI and DLR high flux solar simulators focal spot. For example, detailed spectral measures have allowed developing and validating a mathematical correction for solar simulators flux measurements with a camera (see figure 2). The results have been reported in the SFERA deliverable D12.5: “Solar Simulator Evaluation report” and covers 3 topics: flux characterisation, flux homogenisation, special issues of solar simulators such as lamp ageing or temperature measurements.

Figure 2. Comparison between the solar spectrum and the spectra of the two solar simulators PSI and DLR.

Virtual simulators for future users: preparing the training for the CSP market actors

With a promised important market of CSP plants such as found in AEIA scenarios, it is necessary to develop suitable tools and methods for the training of the future operators of the plants. WP12 within JRA has developed components for such software.
The first type of developed components was optical models in order to determine the thermal output of the solar plant to the process converting energy to electricity. The second type of developed components was advanced thermal models to accurately simulate the behaviour of solar plants such as Parabolic Trough Collectors plant with a molten salts loop when knowing the thermal input as delivered by the first

components. The third and last type of developed components was virtual 3D simulation of a plant, in this case a R&D solar furnace.
Refer to SFERA deliverables D12.2 D12.3 D12.6 and D12.9 for more details, which correspond to both reports and these components as individual software.

Improving the capabilities to achieve ultra-high concentration in CSP facilities
The first milestone planned in WP13 was the development and analysis of the SFERA sunshape measurement system. The system consists of the SAM instrument, a sun photometer and post-processing software. The SAM instrument only measures the spectral radiance within the sun disk and from approx. 0.5° to 7° and it is therefore not a complete sunshape measurement system. One of the tasks of the post-processing software is to transform the spectral information to broadband sunshapes that are required for CSP applications. This step involves radiative transfer calculations based on sun photometric measurements. The overall uncertainty of the SFERA system is a significant improvement compared to previous measurement systems, e.g. the former DLR sunshape camera.
In order to define the impact of the sunshape on the performance of tower plants and simultaneously validate the ray-tracing tools, simulated flux density distribution of single heliostats focused on a target surface of the tower was compared to the flux measured with a CCD camera. The heliostats used for the analysis were measured with deflectometry. The simulation with the DLR software STRAL and the flux measurement showed good agreement. Hence, ray-tracing tool STRAL and its sunshape module have been validated.
CNRS-PROMES investigated the impact of the sunshape on the performance of solar furnaces. Several measurement campaigns at a 2 MSSF (Medium Size Solar Furnaces) with a water calorimeter have been conducted in order to determine how high CSRs lead to lower intercept.
A method was developed to provide information about the sunshape on a global scale utilizing geostationary satellites. Measurements of the satellites of the Meteosat Second Generation (MSG) series were used. The method to derive the circumsolar radiation comprises of two steps. First the particle size and optical depth of the cirrus clouds are determined using the algorithm for the Physical Investigation of Clouds with SEVIRI (APICS). Then a parameterization is applied to convert these parameters into circumsolar radiation. This parameterization was developed using simulations of the sunshape with the radiative transfer model MYSTIC. It was decided to use COCS (algorithm for Cloud Optical properties derived from CALIOP and SEVIRI) as a cloud mask for APICS. The effect of the surface properties on the sunshape was investigated. The algorithm was validated for cirrus clouds using the ground data from the SFERA measurement system.
One and a half years of measurements with the SFERA system from CIEMAT-PSA were evaluated. Not only the SFERA partner CNRS-PROMES, but also Masdar Institute installed a replica of the SFERA system and provided approximately one year of measurements for WP13-T1. CSR histograms and average sunshapes were created for the two sites. The measurements from the two SFERA systems from CIEMAT-PSA and Masdar Institute were also used for ray-tracing studies for exemplary CSP plants. EuroTrough plants and tower plants were modelled at CIEMAT-PSA and Masdar Institute in SPRAY. Significant errors occurred when calculating with so-called standard sunshapes instead of measurements for the instantaneous received power and also for the daily and the yearly heat that is provided to the power block. Ray-tracing with a disk sunshape leads to overestimation of the yearly yield for both sites and both technologies compared to the sunshape time series. Overestimation of 1.8 % was obtained for the tower at CIEMAT-PSA and 3.8 % for Masdar Institute. Even for the troughs the overestimation was

noticeable when calculating with the disk sunshapes. A remarkable overestimation was also found for the tower plant at Masdar when calculating with existing average sunshapes as the SSS (standard solar scan) or the sunshape DLRMean. The overestimation was 1.3 % for DLRMean and 2 % for the SSS. For the tower at CIEMAT-PSA, calculating with the average sunshapes results in relatively small deviations.

The deviations of the yearly yield for the trough in Masdar were smaller than for the tower. The SSS results nearly in the same yearly yield as the sunshape measurements and DLRMean caused overestimation of about 0.4 %.

Based on the ray-tracing results, parameters for the description of the effect of circumsolar radiation on the exemplary plants were studied. The CSR and also the circumsolar contribution are possible parameters for simple models for the description of the circumsolar radiation on the efficiency of CSP plants. When restricting the analysis to a small range of incidence angles or solar positions, a linear relation between the intercept factor and these parameters was found.

Also, the commercially available Black Photon Instruments CSR460 sensor was also investigated in SFERA WP13-T1. The system consists of two pyrheliometers with different field of view. The relative deviations between the two pyrheliometers agree well with the relative deviations expected from the SFERA measurements.

Different sunshape measurement methods are now available and can provide information for CSP projects and research.

Regarding task 2 of WP13, one target was stated on the development of software and procedures to optimally design the secondary concentrator optics in combination with a heliostat field. Both classical tower configurations as beam-down concepts have been regarded. Especially for the optical design of the secondary concentrator, a software tool using a novel approach based on non-uniform rational Bézier-splines (NURBS) was written. By a demonstration it is proved that with this methodology it is possible to fine-tune the geometry of a secondary concentrator (or any other optical device) to the needs of a given special application by varying a sufficiently small number of parameters. Additionally, a generic dimensioning software application has been developed: “VersaDim”. Its design aim was to deliver a “versatile dimensioning” application that would specialize on providing the necessary numerical routines for extreme value finding and rely on separate applications to determine cost function values. Using VersaDim, a NURBS-based secondary concentrator has been adapted to a receiver, trying to maximize the estimated annual yield. It has been found that in this special case, the new NURBS-based concentrator works better than a traditional CPC (compound parabolic concentrator).

The second target of WP13, task 2, was the examination of materials which are actually used or which are candidates for future secondary concentrators. Extensive accelerated ageing tests in different laboratory chambers and consecutive examinations of the sample reflectance were performed. Part of the samples was radiated in a solar furnace and its behaviour under concentrated solar radiation was documented. Additionally, a naturally weathered secondary concentrator was examined and its degradation mechanisms documented.

Further information can be found in the periodic reports and deliverable reports.

Infrastructure improvements to perform durability predictions of CSP components by accelerated aging

The solar spectrum is mainly in the visible spectral range and has a penetration depth of about 20-50 nm in many metals and opaque materials Thus highly concentrated solar beams are ideally suited for surface heating and/or to provide a controllable mean of delivering large flux densities to solid surfaces, where the resulting thermal energy can cause phase changes, atomic migrations, and chemical reactions on a

surface without greatly perturbing the bulk properties; alternatively, the photons may directly interact with species on the surface (as black and/or selective coatings, catalytic coatings, etc.).
The degradation mechanisms of CSP receivers depend on three main factors:
1. The material selection (with its chemical, mechanical, thermal and optical characteristics),
2. The cooling media selection (with its chemical and thermal properties affecting the material corrosion and thermal stress), and
3. The operational conditions (in temperature, concentrated solar flux and cycling), which determines the stress in operation.

The combination of the three selections is associated to a degradation mechanism (mainly corrosion and fatigue). Corrosion usually implies the oxidation of the material and typically a loss of material and structural properties.
On the other hand, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material. Fatigue is strongly associated to the concentrated solar technologies where the daily and cloudy transients may cause fatigue failures.
For materials exposed to highly concentrated and transient solar radiation the degradation of their thermo-physical properties may be quite different than with equivalent thermally aged regular materials. This results from the predominantly superficial effect of concentrated solar radiation. The differences or similarities between these two types of degradations (solar vs. thermal) are rather unknown and the adaptation of the existing concentrating solar facilities to facilitate testing with controlled solar and/or temperature cycles, allow both to give answer to this question and to facilitate the selection of the most durable materials for a certain application and operational conditions, among a set of candidate materials.
WP14 work was divided on two different tasks concerning refurnishing of existing infrastructures for durability tests of materials and accelerated aging; and development of methodologies for material testing under concentrated solar radiation.
At the beginning of the project some improvements have been made on different facilities at the Solar Furnaces of CIEMAT-PSA and CNRS-PROMES to prepare test beds for performing thermal cycling of materials and durability test. Main achievements of this face of the project have been:

- CNRS-PROMES
  - A novel solar aging facility (SAAF, see figure 3) has been developed to perform cyclic irradiance expositions on any material in order to stimulate the aging mechanisms and accelerate them. This facility has been designed by mean of a numerical model to determine the optimal conditions to age the material. It uses a 2-meter-diameter solar furnace which can concentrate the solar radiation up to 16000 times.
  - Design and installation of SESAME and SHADEOK shutters, the latest generation being deployed, offer high moving speeds (in standard ~700 ms for 0 to 100 % concentrator's thermal power output with a possibility to go faster depending on request and study) with high accuracy (about 0.5 % repeatability) and very low dead shadow (below 1% of power intercepted).
- CIEMAT-PSA:
  - Development of porous characterization Lab specially designed to study new volumetric absorbers and configurations, materials, and storage solutions (see figure 4).
  - Refurnishing of the DISTAL-II control System:
    - Installing a new PLC that, on one hand, takes the control of the dish movement to follow the sun over a day and, on the other hand, intercommunicate with the control of the experiment to focus or defocus the dish following the test requirements.

▪ New azimuthal and elevation motors have been installed on the dishes
▪ New Dish movement control system
◦ New test benches for tube type and volumetric receiver materials testing.

Figure 3. SAAF facility at CNRS-PROMES solar furnace. Figure 4. Test Bench for tube type material testing.

Second half of the project was devoted to perform durability tests on both, coated and uncoated nickel based alloy 625 selected materials in facilities at CNRS-PROMES and CIEMAT-PSA, as well as thermal chocking of SiC ceramic volumetric receivers (see figure 5).
From the test results of Task II preliminary guidelines to test several solar absorber materials can be extracted. However, the development of accurate service life time prediction models is a complex task that requires a systematic comparison of naturally aged and accelerated aged material samples. Oftentimes the run-time and operating conditions of materials used in the field are unknown, which makes it hard to derive reliable correlations to the accelerated testing results. Future work is needed in order to validate the preliminary guidelines. Service life time of materials exposed to the operating conditions of solar power plants depends on many environmental parameters. In order to determine simplified accelerated aging tests, each parameter needs to be separated and studied independently. That way, a set of relevant parameters can be identified and a suited test to accelerate specific failure modes can be designed.

Methodology for testing, assessment and characterisation of storage technologies and materials
Characterisation of different storage systems

This task was completed in 2010, in accordance with the Project Work Plan, and the results were summarized in the R15.1 Report on the Methodology to Characterize Various Types of Thermal Storage Systems (Deliverable 15.1 issued: July 2010). This report examines the-state-of-the-art solar thermal storage concepts for electric power generation with a special focus on such characteristics categories as thermodynamics, storage medium properties, heat transfer capability and thermal efficiency, chemical stability and compatibility of materials, design and operational issues. It also includes a statistical analysis of storage operational parameters throughout an annual operating cycle, which shows that in the nominal capacity range of several full load operating hours the storage operation is strongly influenced by daily solar power conditions and its performance appears considerably less efficient in the low-sun season (winter) than in the high-sun season (summer). A certain improvement of the thermal storage efficiency in terms of the annual solar capacity factor can be achieved by increasing the solar multiple that however cause some few percent of solar energy to be unutilized or redirected to an auxiliary purpose. This report can assist the other WP-15 Tasks in developing the methodologies for standardized testing, evaluation and assessment of different energy storage materials and systems.

Figure 5. Evolution of coating absorptance after tests and microstructure evolution of alloy 625 after thermal radiation exposure.

Methodology and definition of standardised testing procedures

Within this task the first approach at international level to define appropriate testing procedures for commissioning thermal storage prototypes, either using sensible or latent heat, designed for solar thermal plants have been defined .
The testing procedures proposed in this task and presented in deliverable 15.2 are the result of the know-how on testing TES prototypes of the different partners involved in the SFERA project WP15 Task 2. The terminology proposed is coherent with the discussions currently ongoing at the Spanish Organization for Standardization (AENOR). This AENOR committee launched a proposal in January 2011 to the International Electrotechnical Commission (IEC) for creating an international committee to draft standards in the field of solar thermal power plants in which thermal storage will be included. The recently created Technical Committee TC-117 started its activities on March 2012. However, while standardization bodies consider thermal storage as a solar thermal electricity (STE) plant component, the activities of this task are focused on thermal storage prototypes so their specific features are taken into account.
The first activity within this task was the definition of all relevant parameters characterizing thermal energy storage systems such as:

• Charging time
• Discharging time
• Charging power
• Discharging power
• Mean thermal power
• Storage capacity • Storage level
• Stored energy
• Thermal losses
• Idle thermal losses
• Thermal efficiency

For all of these parameters precise rules for the experimental determination have been defined, applicable to all relevant kinds of thermal energy storage systems. As mentioned above deliverable 15.2 has meanwhile served as a basic document for the international standardization activities in the present technical committee TC-117 of the IEC.

Methodology to characterize storage materials

In thermal energy storage (TES) units, the energy can be stored by mean of various kinds of physical phenomena involving thermal effects: sensible heat, latent heat, adsorption, absorption, thermo-chemical reactions. In the practical field of Concentrated Solar Power (CSP), current industrial TES units are based upon sensible heat using liquid phase materials (such as molten salts) or solid phase materials at high temperatures (such as refractory ceramics). Major efforts are made to develop liquid-solid latent heat TES highlighted by today by recent pilot scale experiments. The aim of this task was to gather the various aspects related to the properties of TES materials. According to the above considerations, the work has been focused on sensible and latent heat TES materials only. Conventional currently considered

properties such as density or thermal capacity are taken into consideration but not only at room temperature but considering the whole temperature range under operation. Other properties, which are usually not considered despite their real importance, such as thermo-mechanical behaviour or the fatigue of the material under thermal cycling are also included and have been especially studied. A particular attention has been also given to porous materials with a specific devoted chapter.
Within the project all relevant properties of state-of-the-art storage materials have been identified. For all these parameters appropriate measurement techniques have been identified and described. The specific requirements for the application for thermal energy storage materials are outlined and described in detail in deliverable 15.3.

New Measurement System for PCM storage

In the frame of Task 4/WP15, a lab-scale setup based upon the “electric resistance approach” has been developed and put into operation to measure the charging/discharging status of a phase change material (PCM) storage system. PCM storage systems are favourable for direct steam generation (DSG) plants. At the moment, temperature sensors detect the charging/discharging status of these systems. However, during charging/discharging the system has a temperature plateau and is isothermal. For this reason, the charging status, defined as the ratio of the mass fraction of liquid PCM to the total PCM mass, cannot be detected directly. As a consequence, WP15 Task 4 aimed to identify alternative parameters and methods to determine the charging status of PCM storage systems.
For high-temperature PCM systems, other sensor systems than temperature sensors have not been previously considered. Hence, work reported under SFERA project outlines an overview and classification of alternative methods. Existing alternative PCM measurement methods in the low temperature range are reviewed (e.g. ice storage). The adaptation of these methods to the high temperature range is assessed. Intrinsic properties, such as optical transparency, electric resistance and density, of high-temperature PCM (anhydrous salts) are evaluated. The selected alternative measurement approach detects differences between the solid and liquid phase of the PCM in terms of the electrical resistivity and the filling level due to density changes. One major challenge of this approach is the electrode design in the high-temperature environment. Lab-scale tests with several different electrodes have been performed.
Within the project a novel electrode was developed (patent pending, see figure 5). The design allows for the integration of the electrode in a PCM storage system. For the electric resistance approach suitable measurement parameters (e.g. frequency, voltage) were identified. Within the project, a signal generation and data acquisition unit was developed. Also, a graphical user interface within the control software of the PCM-storage was programmed. A lab-scale experimental setup clearly demonstrated differences in the electrical conductivity of several orders of a magnitude between the solid and the liquid phases of high-temperature PCMs. The feasibility of the detection of the charging/discharging status on larger-scale systems was proved. Measurements with electrodes on a prototype storage system with about 160 kg PCM demonstrated the approach.

Figure 6. Photograph of novel high-temperature electrode.

Another major task was the integration of the alternative PCM measurement method with several electrodes in an existing prototype latent heat storage system. A customized electronic circuit included sinus signal generation, signal processing, multiplexing of electrodes and data acquisition was designed. This design not only included hardware, but also some major software developments. We tested the alternative PCM measurement method using several electrodes in a PCM-prototype storage system with thermal oil as a heat transfer fluid and sodium nitrate with a melting temperature of 306 °C as a PCM. Measurements with the signal generation and data acquisition unit and the PCM prototype storage system clearly demonstrated the feasibility to detect the charging/discharging status with the alternative PCM measurement method.

Methodology for evaluation and assessment of different energy storage technologies

Thermal energy storage (TES) is a key technology for renewable energy utilization and the improvement of the energy efficiency of heat processes. Especially for concentrated solar thermal power plants (CSP plants), TES is essential, because it makes power produced by CSP plants dispatchable. In the medium to high temperature range (100 - 1000 °C), only limited storage technology is commercially available, being a 2-Tank molten salt storage and steam accumulators. However, various new storage technologies are currently under development for the very specific requirements of the different applications [Laing, D., Steinmann, W. D., Tamme, R., Wörner, A., Zunft, S. (2012) Advances in thermal energy storage development at the German Aerospace Center (DLR). Energy Storage Science and Technology, 1, 13-25; Gil, A., Medrano, M., Martorell, I., Lázaro, A., Dolado, P., Zalba, B., Cabeza, L. F. (2010) State of the art on high temperature thermal energy storage for power generation. Part 1 - Concepts, materials and modellization. Renewable and Sustainable Energy Reviews, 14(1), 31-55, Medrano, M., Gil, A., Martorell, I., Potau, X., Cabeza, L. F. (2010) State of the art on high-temperature thermal energy storage for power generation. Part 2 - Case studies. Renewable and Sustainable Energy Reviews, 14(1), 56-72]. The aim is the development of cost effective, efficient and reliable thermal storage systems, adapted to the applied heat transfer fluid and the required temperature range of the CSP plant (see Table 1).

Table 1. Heat transfer fluids with typical operation ranges

HTF	Max. temperature [°C]	Pressure range [bar]
Synthetic oil	400	15 – 40
Water/steam	800	30 – 160
Molten salt	560	1
Air	1000	1 - 15

In the evaluation and assessment conducted within SFERA the storage systems listed in Table 2 and their combinations are addressed. However, not every storage system can be used in combination with each HTF. For this reasons certain knowledge of the systems is needed. The objective of the web-application tool developed is to give the respective user the possibility to check out which storage systems are feasible for the specific application and to give some hints about the strength and weakness of the specific systems concerning different evaluation parameters.

Table 2. Storage systems included

Storage System	TMax [°C]	TMin [°C]

2-Tank Molten Salt (indirect) 560 270
2-Tank Molten Salt (direct) 560 270
Thermocline (indirect) 400 270
Thermocline (direct) 560 270
Concrete 500 20
Cell Flux 800 20
Packed Bed 1000 20
PCM 350 20
Steam Accumulator 300 100

Of course this list cannot cover all storage concepts currently under development, so it is only a selection. For example, to date, thermochemical storage has not been included in this evaluation, due to the minor state of maturity, however, development is progressing and for future systems this technology shows high potential.
As output the program gives suggestions of different storage systems for the parameters provided by the user. Within the program the storage systems are evaluated in two ways:
- Qualitative evaluation.
- Quantitative evaluation.

Qualitative evaluation
In this case the user will get an evaluation table with all suggested storage systems. Each system is evaluated by different criteria, such as:
- Storage density.
- Constancy (temperature, pressure).
- Technical maturity.
- Local share.

The evaluation system is carried out as follows:
Table 3. Evaluation system.
Criteria Sign Evaluation
Storage density + Storage density > 80 kWh/m^3
o 40 kWh/m^3 <= Storage density <= 80 kWh/m^3
- Storage density < 40 kWh/m^3
Constancy (temp., pressure) + Temperature and pressure constant
o Pressure or temperature decreases
- Pressure and temperature decreases
Technical maturity + Commercial
o Prototype
- Labscale
Local share + Well feasible with local possibilities
o feasible with local possibilities
- Not good feasible with local possibilities

From every qualitative evaluated storage system the user can get more detailed information from a table. Such as:
- System schematic.

- Additional information as far as available.
Quantitative evaluation
For this evaluation the user is able to choose between a result related to the storage material volume in kWh/m^3 and a result in related to the storage material mass in kWh/t. Figure 6 shows an example.

Figure 7. Exemplary result in kWh/m^3

Potential Impact:
Development of SFERA project has involved three principal activities: Networking, Trans-national Access and Joint Research Activities. Each one has shown a potential impact according to the final results achieved.
Networking activities has involved not only the organization of international conferences on CSP technology which addressed a global audience; but also training courses and schools' attaining the creation of a common training framework, providing regularized, unified training of young researchers in the capabilities and operation of concentrating solar facilities.
Joint Research Activities have achieved a common level of high scientific quality and service through a synergistic approach. During the consecution of SFERA project it has been generated an up-to-now no existing European identity for Research on Concentrating Solar Technologies. Scientific and technological excellence have been strengthened due to an envisaged harmonization and the most effective use of large-scale infrastructures, as well as the establishment of virtual working groups and an extended dissemination strategy. Finally highlighted impact has been detected in the identification and integration of further research and possible industry partners as well as an obvious long-term commitment of the key partners, which show a significant impact on the European Research Area, too.
Finally, the achievement of Transnational Access activities within the frame of SFERA project has unified all European large scale infrastructures and makes them available to European Researchers. This 'open-door' policy has shown to revert on the benefit of the own research groups and facilities themselves, as usually the visiting scientists provide new ideas for solar research and new technical possibilities and advances to the well-established operating procedures. They normally come from non-solar scientific communities, then stimulating the way of thinking of the facilities' researchers, helping them to identify new possible applications for the solar energy. Access activity have forced facilities' researchers to keep the facilities up and running, optimizing the operating and maintenance procedures and, last but not least, enriching culturally as European citizens by sharing our working days with people from 27 countries across Europe.

Organization of training courses and schools
The objectives and impacts of this WP were:
- To present SFERA solar facilities to potential users including basic knowledge needs for preparing a proposal and experimental data interpretation, and
- To transfer knowledge gained in the project to students as they are researchers and practitioners of the future and to engineers from industry.
These objectives have been reached with the organization of four training courses and schools:
Date Organizer Topic Participants
June 2010 PROMES-CNRS Radiation in Solar Systems 33
March 2011 ETH Solar Fuels & Materials 49

June 2012 PSA-CIEMAT Solar Thermal Electricity Generation 36
May 2013 DLR Measurement Tools & Standardization Aspects for Concentrating Solar technologies 40

With the SFERA Schools, it has been possible to create a common and rich training framework for people external to the SFERA project. In total, 44 lecturers have been involved in the schools. Young and senior researchers from the consortium and operating in the field of concentrating solar facilities have successfully managed to transfer their knowledge to the public. With the presence of industrials in the lecturers, emphasis was given on case studies and practical experience, hence providing a practical point of view and creating a culture of innovation. The school has also nurtured the sharing of experiences and best practices between the school participants and helped to make new collaborations happen.

Internal and external communication: Organization of meetings, workshops and conferences
The main objective of this WP is to organize common meetings and colloquia in order to inform SFERA participants of main results, proposals and cooperation domains. Concerning a more general audience, the objective is to disseminate results of general interest in the scientific and industrial communities, and towards the general public. A key tool for both purposes is the construction and maintenance of a web site that contains the main open information about the project and all deliverables and documents generated by SFERA.

The objectives for this WP have been reached thanks to the organization of different communication actions. Five conferences have been organized:
- Three workshops at the largest CSP international conference SolarPACES
- One exhibition booth at SolarPACES 2013 and one at CSP today Seville Conference which gathers the largest European community of industry. The aim was to promote there the results among industries in order to boost innovation and the take-up of potential SFERA results.

SolarPACES 2010 France SolarPACES 2012 Morocco CSP Today Seville 2013 Spain
SolarPACES 2011 Spain SolarPACES 2013 United States

The three conferences have been a success and have certainly attracted new SFERA users for the access to the installations. It has informed a wide public about the actions performed within the project and has had a great attendance rate. The SolarPACES conference attracts around 900 participants each year and for the CSP today Seville conference, this is around 400. More dissemination has been possible with the exhibition booths in 2013. We have edited a USB flash drive with all public documents and deliverables in order to widely disseminate the results of SFERA.
For internal communication, four doctoral colloquiums have been organized for the PhD students of the partners. This action is focused on strengthening the cooperation within the partners of the project in order to improve the services to the users. One Colloquium is organized every year in order to present the recent results of PhD students preparing their thesis in the various laboratories members of the project and to extract from these results what could be useful for improving services of solar facilities. The topics approached are Thermal Storage technologies, Solar Fuels, Solar Desalination processes, Materials for

concentrating technologies, Point focusing systems, Linear Focusing systems, and Fundamental research.

2010 PROMES-CNRS 44 PhD Students
2011 ETH 37 PhD Students
2012 PSA-CIEMAT 38 PhD Students
2013 DLR 46 PhD students

Other actions that have been carried out are the following:
- Four newsletters (e-publication) to be distributed to users and potential users.
- Two SFERA project brochures have been edited as promotional materials: one to provide an overview of all SFERA activities and the other one to make the promotion of success stories within the Access activities.
- An ontology for CSP has been developed to define a common terminology for CSP components and systems in order to facilitate Multilanguage search of information. A glossary with more than 1000 key words in English and related to CSP has been developed.

The general aim of WP3 is to increase the public visibility and awareness of SFERA and thanks to this WP, it has been a success. Announcements in scientific journals and interviews online have also been carried on (SFERA flushes out ground-breaking CSP research). Also, a certain number of peer-reviewed publications have been published to present the scientific results (see section 4.2).
All Networking documents are available online as part of the dissemination activities.

Figure 8. SFERA Final meeting and closing conference at PSA

Exploitation of results
During the project developed sunshape measurement methods can be used at many sites in order to create a bigger circumsolar radiation data base and to improve the accuracy of CSP plant yield predictions and CSP performance evaluation. The investigated systems are already commercially available, and their application by thirds already started during the SFERA project.
Based on the exemplary results for the investigated CSP plants, the effect of circumsolar radiation on the plant yield in hazy regions can be estimated roughly. The raw data from the SFERA systems are available online and can be used also for other studies - be it for solar energy applications or atmospheric science. The correct processing of time series of circumsolar radiation data is now possible with the software SPRAY. Together with the now available sunshape measurement systems, this will further improve the accuracy of CSP plant yield assessment.

For further information, please visit our website: http://sfera.sollab.eu/

List of Websites:

http://sfera.sollab.eu/

Related documents

final1-sfera-final-report.pdf

Last update: 20 April 2015

Permalink: https://cordis.europa.eu/project/id/228296/reporting

European Union, 2025