GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

PLATAFORMA SOLAR DE ALMERÍA

ANNUAL REPORT 2022


ALMERÍA
PLATAFORMA SOLAR
DE ALMERÍA
TABERNAS
ALMERÍA

Publication available in catalogue of official publications

ISSN: 2659-8175
NIPO: 832-20-003-4

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2 General Presentation

The Plataforma Solar de Almería (PSA), a department of the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), is the largest concentrating solar technology research, development, and test centre in Europe. PSA activities are integrated in the CIEMAT organization as an R&D division of the Department of Energy.

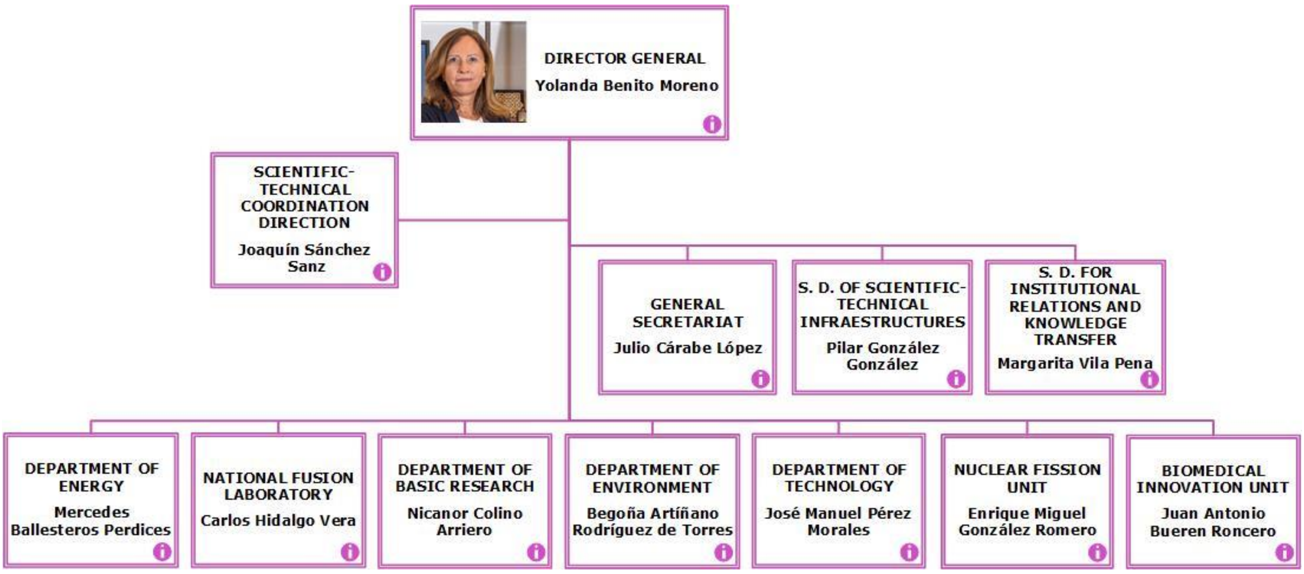


Figure 1. Integration of the PSA in the CIEMAT organization

The following goals inspire its research activities:

- Contribute to establishing a sustainable clean world energy supply.
- Contribute to the conservation of European energy resources and protection of its climate and environment.
- Promote the market introduction of solar thermal technologies and those derived from solar chemical processes.
- Contribute to the development of a competitive Spanish solar thermal export industry.
- Reinforce cooperation between business and scientific institutions in the field of research, development, demonstration, and marketing of solar thermal and solar photochemical technologies.
- Strengthen cost-reducing techno-logical innovations contributing to increased market acceptance of solar thermal technologies.
- Promote North-South technological cooperation, especially in the Mediterranean Area and Latin-American Community.
- Assist industry in identifying solar thermal and solar photochemical market opportunities.

Since 2021, research activity at the Plataforma Solar de Almería has been structured around seven R&D Units under a Technical Coordinator, plus a strong unit to manage and coordinate all facilities and laboratories, namely the PSA Management Unit. In addition to the different horizontal services (IT services, Instrumentation, Maintenance, Civil Engineering Operation, etc.), two additional facilities

(METAS and LECE), physically allocated within PSA but with associated personnel formally outside PSA structure, are also included in this PSA Management unit.

Figure 2. Aerial view of the PSA

The seven R&D Units are as follows:

a. *Line-Focus Concentrating Solar Thermal Technologies*. Devoted to testing, evaluating and developing components and applications for linear focusing solar concentrators, its scientific and technological objectives are:
   - Advanced heat transfer fluids with lower environmental footprint for working temperatures higher than 400 °C.
   - Cheaper collector designs and innovative plant configurations achieving better use of solar energy resource and technologies.
   - More efficient, cost-effective and reliable components (e.g. receiver tubes, mirrors and flexible connections.
   - Integration of solar thermal power plants with other technologies.
   - New applications for linear focusing concentrating technologies.

b. *Point-Focus Concentrating Solar Thermal Technologies*. Target focused on providing technical assessment to the industry stakeholders together with the research and innovation related to power tower technologies such as the measurement of concentrated solar flux, R&D of new fluids and receivers, optical and numerical analysis, its scientific and technological objectives are:
   - Development of receivers for mean solar fluxes >1MW/m^2 and thermal efficiencies higher than 85 % for temperatures above 600 °C.
   - New innovative working fluids with operating temperatures above 600 °C for Rankine cycles, and above 750 °C for unfired Brayton cycles.
   - Self-calibrating and cheaper heliostats, below 90 EUR/m^2 (installed).

- High precision heliostat field and automated control for long focal distance and/or high temperature applications up to 1,200°C.
- Innovative plant configurations achieving better use of solar energy resource and technologies.
- High degree of automation of condition monitoring of all relevant plant parameters to optimize O&M, including virtualization of plants, augmented reality and remote supervision.
- Provide solutions for onsite measurements to characterize the total solar receiver's surface in terms of temperature and concentrated solar irradiance, and solar radiation extinction within the solar field.
- New applications for point-focus solar thermal technologies.

c. *Thermal Energy Storage for Concentrating Solar Thermal Technologies.* Addressing the design, testing and optimization of thermal storage systems for temperatures above 120°C up to 800°C, its scientific and technological objectives are:
    - Feasibility of materials for thermal storage systems.
    - Testing and characterization of prototypes, components and equipment for thermal storage systems.
    - Design and optimization of thermal storage systems following a holistic approach.
    - Integration of thermal storage systems in different applications.

d. *Materials for Concentrating Solar Thermal Technologies*. Addressing the development and testing of new or improved materials for CST solar technologies or their applications, as well as thermal treatment, aging or modification of materials, its scientific and technological objectives are:
    - Development and testing of advanced materials and coatings for CST technologies (primary and secondary reflectors, absorbers, receiver covers, receiver particles, etc.) for increased robustness, efficiency and long-term durability under operating conditions in harsh climates or environments.
    - Development and standardization of suitable methodologies for the optical characterization and lifetime prediction of materials for CST technologies.
    - Development and testing of cost-effective cleaning methods to reduce the water consumption in the O&M activities.
    - Usage of CST technologies for materials' treatment, including thermal treatment, synthesis, characterization, aging and processing of materials at high temperature, by surface or volume treatment (with solar receivers or reactors).
    - Development and testing of nanostructured materials to enhance thermal conductivity.
    - Development of catalysers for electrochemical and solar thermal applications to produce fuels (hydrogen, ethanol, methanol…).

e. *Solar Thermochemical Processes and Technologies*. This includes high temperature processes based on concentrated solar energy to hydrogen and other valuable and energy intensive raw materials production, its scientific and technological objectives are:
    - Solar-to-fuel conversion efficiencies ≥ 15 %, with the integration of heat recovery.
    - Proof-of-concept operation of solar fuels production reactors, comparable to "traditional" chemical industrial plant operation.
    - Development of components for high solar concentration, especially those with a significant impact on the performance of the technology (solar receivers, secondary concentrators, windows, etc.).

- Use of materials that do not exhibit toxicity and/or corrosion issues, especially under the extreme conditions that many thermochemical cycles require.
- 1 MW (H_2 production) scale demonstrator with at least 1,000 hours of operation time.
- Explore custom-made solar field options capable of achieving the high temperatures required on high-efficiency receivers/reactors.
- Integration of receiver/reactor concepts to the requirements of industrial processes, such as lime, aluminium, etc.

f. *Solar Thermal Applications.* Devoted to the development and evaluation of solar thermal technology applications in industrial processes, including desalination and brine concentration, its scientific and technological objectives are:
   - Development and evaluation of advanced solutions to reduce energy and water consumption, operation and maintenance costs of solar thermal applications.
   - Development of design, simulation and optimization tools for solar thermal application systems.
   - Integration of solar thermal energy in hybrid process heat applications.
   - Optimization of solar fields to improve the efficiency of low temperature heat applications.
   - Design and implementation of solar thermal separation solutions for desalination, water treatment, brine concentration and product recovery.
   - Integration of desalination technologies in concentrated solar power plants for water and power cogeneration and water saving.

g. *Solar Treatment of Water*. Focused on exploring the chemical possibilities of solar energy, especially the potential for water decontamination and disinfection and the production of solar fuels by means of photochemical processes, its scientific and technological objectives are:
   - Design, improvement and optimization of solar photo-reactors.
   - Technologies at the edge of the knowledge based on a combination of reductive and oxidative photochemical processes for the elimination of particularly complex and persistent contaminants.
   - Combination of advanced solar photo-oxidation processes with other innovative technologies for decontamination and disinfection of all kinds of wastewater for reusing purposes (own industrial processes or crops irrigation).
   - Production of fuels and artificial photosynthesis by solar photocatalysis.
   - Residues valorisation. Combination of separation technologies and solar processes to achieve the recovery of nutrients from wastewaters for their subsequent use in agricultural activities.
   - Comprehensive systems analysis. Techno-economic assessment and Life cycle analysis for new developed technologies and/or applications.

Supporting these R&D Units are the Direction and Technical Services Units mentioned above. These units are largely self-sufficient in the execution of their budget, planning, scientific goals, and technical resource management. Nevertheless, the four R&D units share many PSA resources, services, and infrastructures, so they stay in fluid communication with the Direction and Services Units, which coordinate technical and administrative support services. For its part, the Director’s Office must ensure that the supporting capacities, infrastructures, and human resources are efficiently distributed. In addition, the Director’s Office channels demands to the different general support units located at CIEMAT’s main offices in Madrid.

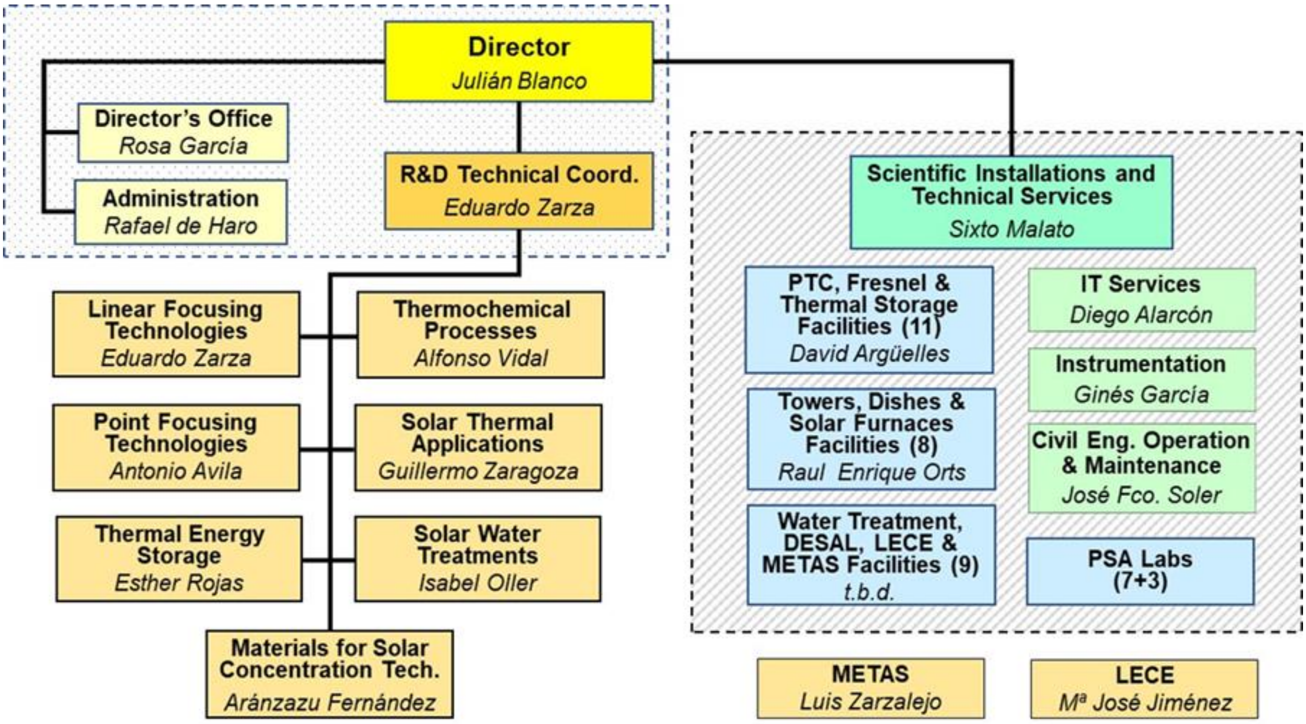


Figure 3. Internal organizational structure of PSA in 2022

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 142 people that as of December 2022 made up the permanent staff lending its services to the Plataforma Solar de Almería. In addition to this staff, there is a significant flow of personnel in the form of visiting researchers, fellowships and grants handled by the Director's Office. Out of the 132 people who work daily for the PSA, 71 are CIEMAT personnel, 15 of whom are located in the main offices in Madrid.

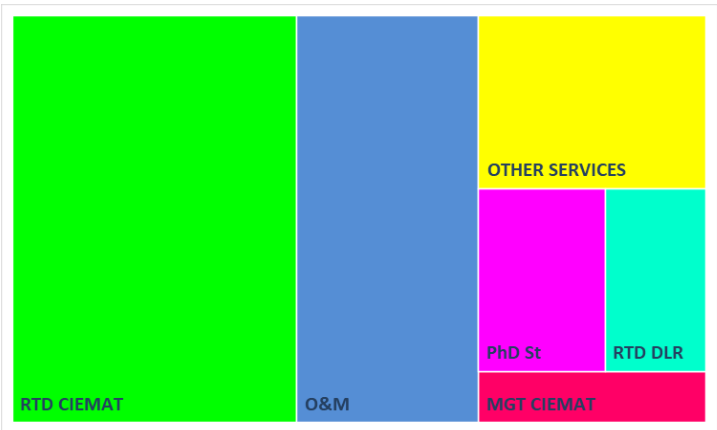


Figure 4. Distribution of permanent personnel at the PSA as of December 2022

In addition, the 8 people who make up the DLR permanent delegation as a consequence of its current commitments to the Spanish-German Agreement also make an important contribution.

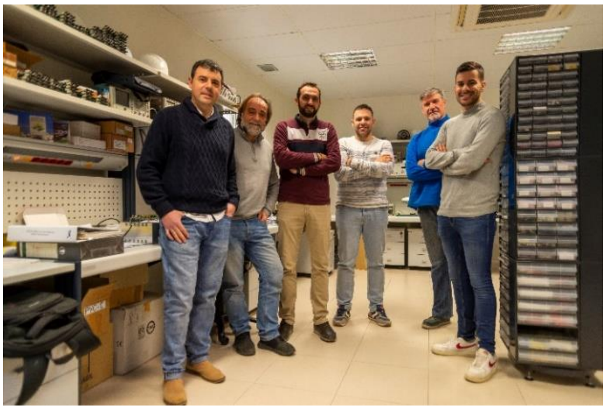
The rest of the personnel is made up of a no less important group given the centre's characteristics. They are the personnel working for service contractors in operation, maintenance and cleaning in the different facilities. Out of these 34 people, 17 work in operation, 13 in maintenance and 4 in cleaning. The auxiliary services contract is made up of 5 administrative personnel and secretaries, 7 IT technicians for user services, and another 5 people from the security contract, which makes a total of 17 people.

The effort CIEMAT has made during the last several years to provide the PSA with the necessary human resources should be emphasized. This continued effort is allowing us to undertake our task with greater assurance of success.

The PSA operating budget in 2022 totals 3.7M Euros (not including R&D personnel or new infrastructure).

Direction Unit

Administration unit



Instrumentation unit

IT Services unit

Infrastructure unit

Figure 5. Personnel at the PSA as of December 2022 (continue in next page)

Operation unit

Maintenance unit

Figure 5. Personnel at the PSA as of December 2022 (first part in previous page)

3 Line-focus Concentrating Solar Thermal Technologies Unit

Introduction

The aim of the activities carried out by the Line-focus Concentrating Solar Thermal Technologies Unit is the testing, evaluation and development of components and applications for linear focusing solar concentrators (i.e., parabolic troughs and linear Fresnel systems), including not only electricity generation but also industrial process heat applications. There is a great synergy between this Unit and the PSA Units devoted to point-focus technologies and materials because there are evident cross-cutting activities among them (e.g., durability analysis and optical coatings).

Additionally to the techno-scientific activities performed in specific R+D projects, this PSA unit has also devoted in 2022 a great effort to dissemination activities, by participating (in person or virtual) in international conferences, workshops, seminars and Master courses to promote the knowledge about line-focus concentrating solar thermal technologies and their applications.

This PSA unit has continued its activities in the field of developing, testing, and evaluating components for line-focus solar collectors (SOLTERMIN project and bilateral contracts with Spanish companies), developing new techniques, measuring capabilities and test facilities (SFERA-III project, LAVEC), testing a new silicone fluid for parabolic troughs (SING and Si-CO projects), modelling and simulating power plants with parabolic-troughs in order to analyse their integration with other renewable energy sources for power generation (POSYTYF project) and contributing to the development of standards and guidelines for the testing and evaluation of components for solar thermal power plants (participation in the development of new standards in the IEC TC117 and AEN/CTN 206 SC117 committees, and also through Si-HTF Guideline and Si-HTF Standard projects financed by SolarPACES). The collaboration with the industry and other research centres related to system simulations or round robin tests continued within the framework of partnership agreements or technical services in 2022 (e.g. service agreements signed with ELESA and IEECAS).

List of projects this PSA Unit has been involved in

- Soluciones termosolares para integración en procesos industriales, SOLTERMIN
- Solar facilities for the European Research Area - SFERA-III
- Silicone fluid maintenance and operation, SING
- POwering SYstem flexibiliTY in the Future through Renewable Energy Sources, POSYTYF
- Silicone Based HTF in Parabolic Trough Applications – Preparation of an international standard, Si-HTF Standard
- High performance parabolic trough collector and innovative silicone fluid for CSP power plants, Si-CO.
- Development of a guideline for Rotation and Expansion Performing Assemblies, REPAs (REPA-Guideline) and REPA testing at the HTF test loop
- Desarrollo de concepto innovador de planta termosolar (NEOSOLAR)

The Head of this unit has also participated in the European projects: "Implementation of the Initiative for Global Leadership in Solar Thermal Electricity' (HORIZON-STE) and "Solar Twinning to Create Solar Research Twins' (Solartwins).

4 Point-Focus Solar Thermal Technologies Unit

Introduction

The objective of the unit is to promote and contribute to the development of Point Focus technologies, mainly Central Receiver Systems, for the utilisation of concentrated solar radiation for both electricity and process heat generation for applications demanding temperatures above 400 – 500 °C. The main lines of research during 2022 have been focused on: 1) the commitment with volumetric receiver technology; 2) the development, testing and evaluation of new heliostat concepts and designs; 3) the improvement in the measurement of variables of control in real time for power tower plants; 4) the study and application of artificial intelligence to decrease the CAPEX and OPEX of central receiver systems; and 5) the assistance to industrial stakeholders to achieve an effective development of the technology.

Following the completion of the European NEXTOWER project in June 2021, an extended experimental campaign on the developed volumetric receiver with two different absorber configurations was carried out on the CESA-1 tower during the summer of 2022. In addition, the main tasks of the SOLTERMIN project were completed. In parallel, and thanks to the Unit's extensive experience in heliostat design and testing, the evaluation of the ATH146 heliostat was carried out and the innovative self-aligned heliostat was deployed. It is noteworthy that three projects were granted during 2022. Firstly, the national INTECSOL project, led by the Material Unit, which deals among other tasks, with improvement and enhancement of volumetric receivers and self-aligned heliostats. Secondly, the national HELIOSUN project, which is focused on the acquisition and development of a large solar extinction database as well as the application of Artificial Intelligence to improve the operation and management of heliostat solar fields. And thirdly, the ERA-Net LEIA project, which will implement smart solar field and receiver control and operation solutions in central receiver systems. Both HELIOSUN and LEIA projects are led by the Point Focus Unit. Moreover, the AdaptedHelio project continued with the operation and measurement of air velocity profiles on the solar field of CESA-1 facility. Finally, Point Focus Unit is clearly aligned on solving the measurement issues at commercial power tower plants, especially those related with the solar atmospheric attenuation and with the measurement of high solar irradiance. At this respect, a new PhD candidate is expected to start during first semester of 2023 and it is worth to mention that during 2022, the second commercial atmospheric extinction measurement system developed at CIEMAT-PSA has been implemented in a commercial tower plant of 100 MWe in the Mohammed bin Rashid Al Maktoum solar park in Dubai (United Arab Emirates).

List of projects the group has been involved in

- Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower systems – NEXTOWER.
- Solar facilities for the European Resarch Area – SFERA-III.
- Solar field measurements to Increase performance – LEIA.
- Soluciones termosolares para integración en procesos industriales – SOLTERMIN.
- More efficient Heliostat Fields for Solar Towers – HELIOSUN.
- Innovaciones tecnológicas para la mejora de la viabilidad de las plantas termosolares de concentración – INTECSOL.

- Wind adapted heliostat, based on field measurements in the heliostat field and validation of wind tunnel measurements – AdaptedHelio.
- Desarrollo de concepto innovador de planta termosolar de colector cilindroparabólico de tubo fijo y circuito de sales con almacenamiento térmico mediante termoclina acoplada a sistema de generación de hidrógeno verde – NEOSOLAR.
- Helióstato ATH146.

Solar extinction measurement system commercialization – Ref. 8510/2018.

5 Thermal Energy Storage Unit

Introduction

During 2022 researchers of this unit have been actively working in international, national and regional funded projects, listed below. Apart from those, several technical services have been provided to companies, mainly dealing with testing and characterization of components and equipment for molten salt loops.

The staff of the Thermal Energy Storage Unit actively participate as experts in several scientific networks (Energy Storage JP of EERA, and Task III of SolarPACES TCP of the IEA, task 67/40 SHC/ECES TCPs) and both national (AENOR-GT3) and international (IEC- CTN 206/SC 117/GT 03 and ASME-PCT52) standardization committees.

The activities of this unit deal with all aspects involved in the development, verification and optimization of efficient Thermal Energy Storage Systems (TESS) by:

- Proposing new storage media and characterizing some of their properties.
- Testing components for molten salt circuits (valves, pressure gauges, vertical pumps, heat tracing, etc.).
- Designing new heat storage concepts with known storage media considering both the specific application and the thermal energy source.
- Testing novel modules for energy storage, both sensible and latent, even under real solar conditions.
- Modelling the behaviour of TESS, with own and commercial programs.
- Optimizing the operation strategies of TESS in order to take the maximum advantage of the stored energy

List of funded projects the unit has been involved in

- Smart Thermal Storage for Decarbonisation of Energy Sector, STES4D
- Storage Research Infrastructure Eco-System, StoRIES
- Small-Scale Solar Thermal Combined Cycle, POLYPHEM
- Solar facilities for the European Research Area - Third Phase, SFERA-III
- Concentrated solar power in the transport sector and in heat and power production, ACES2030
- Energy storage solutions based on conCRETE, E-CRETE

Figure 6. Researchers of Thermal Energy Storage Unit in 2022

6 Materials for Concentrating Solar Thermal Technologies Unit

Introduction

The research activities performed in this PSA Unit are focused on the development, characterization and testing of advanced materials and coatings for CST technologies (primary and secondary reflectors, absorbers, receiver covers, receiver particles, etc.). The aim is to increase robustness, efficiency and long-term durability under operating conditions in harsh climates or environments, as well as the usage of CST technologies for materials' treatment and processing. This usage includes thermal treatment, synthesis, characterization, aging and processing of materials at high temperatures, by surface or volume treatment (with solar receivers or reactors). In particular, during 2022 we have worked on the development and testing of selective and non-selective absorbers (SOLTERMIN and INTECSOL projects), development of a non-selective high-temperature solar absorber for receiver particles (COMPASSCO2 project), development and testing of antireflective coatings for windows used in point focus receivers (SOLTERMIN project), development of antisoiling coatings both for solar reflectors and glass solar tubes (INTECSOL project), testing of solar reflectors under several outdoor environments as well as accelerated aging conditions (SOLTERMIN, SOLARTWINS and GREENCOAT projects), accelerated aging of materials for CST technologies under high radiation fluxes in solar furnaces (SFERA-III, SOLTERMIN, HiPIMSOLAR and HIDROFERR projects), development of a proper methodology to characterized soiled reflectors (SFERA-III) and standardization of the methodology to measure optical properties of components for CST technologies (reflectors and receiver particles) (participation in the development of new standards in the IEC TC117 and AEN/CTN 206 SC117 committees and also through Soiling and Particle projects financed by SolarPACES).

In addition to the work related to the funded projects previously mentioned, we have worked on three PhD thesis projects. Within the first one, a procedure is being developed for the measurement of degradation of primary reflectors within the solar field in commercial plants. The investigation addresses the evaluation of commercial reflectometers, in-field microscopic analysis for the early detection of degradation and optical systems for the determination of the degraded area of reflectors. Within the other PhD thesis project, a design of new optical coating materials that guarantee a high absorption efficiency (absorptance > 95 %), low emission losses and good durability in extreme temperature and weather conditions is under study with a view to their future application in high temperature solar thermal plants. Finally, a third PhD thesis project started by the end of 2022, with the main goal of developing antisoiling coatings that might be applied both on solar reflectors and glass solar tubes.

List of projects the unit has been involved in

- Components and materials' performance for advanced solar supercritical CO_2 power plants, COMPASsCO2.
- Solar facilities for the European Research Area, SFERA-III
- Solar Twinning to Create Solar Research Twins, SOLARTWINS
- Soluciones termosolares para integración en procesos industriales, SOLTERMIN
- Impulso a tecnología de producción H2 por vía termosolar mediante desarrollo y validación de nuevos materiales para receptores cerámicos de durabilidad extendida, HIDROFERR

- Nuevos recubrimientos nanoestructurados para absorción eficiente de la radiación solar en dispositivos de concentración, HIPIMSOLAR
- Soiling measurement of solar reflectors
- Characterization of optical properties of particles for CSP
- Innovaciones tecnológicas para la mejora de la viabilidad de las plantas termosolares de concentración, INTECSOL
- Desarrollo y análisis de la vida útil de recubrimientos protectores sin plomo para espejos en plantas de energía solar térmica), GREENCOAT

(a)

(b)

Figure 7. Unit Staff at CIEMAT Headquarters in Madrid (a) and at Plataforma Solar de Almería in Tabernas (Almería) (b)

7 Thermochemical Processes for Hydrogen and Feedstock Production Unit

Introduction

The strategic task of the Group of Solar Hydrogen and solarisation of industrial processes addresses the demonstration, scale-up, of solar-driven thermochemical processes for the production of fuels (e.g., hydrogen, syngas) and industrial processes (e.g., cement, metallurgy, etc), by exploiting their know-how to develop suitable solar reactors and components and to qualify reactor materials to transfer the results to larger scales close to industrial size.

During 2022, our researchers have been actively working in international, national and regional funded projects, listed in the following paragraph. Through its experts, the Solar Fuels Unit participates actively in several scientific networks: Task II of SolarPACES TCP of the IEA, t, Spanish association for Hydrogen -AeH2-). The Unit has been recently Invited to participate in the development of a new task on renewable hydrogen production, within the IEA Hydrogen TCP framework (Tasks in definition - IEA Hydrogen).

A recent approach is to use thermochemical processes on the Moon and Mars to produce vital resources in space.

The lines of activity are concentrated in the following fields:

- Development of hybrid solar/fossil endothermic and thermochemical cycles processes for hydrogen production with concentrated solar energy.
- Technological feasibility of the use of solar thermal energy as the energy supply in high temperature industrial processes.
- Characterization of materials and components for solar reactors under extreme conditions.
- A recent approach on track is to use thermochemical processes on the Moon and Mars to produce vital resources in space.

List of projects the unit has been involved in

- Solar facilities for the European Research Area - Third Phase, SFERA-III
- Concentrated solar power in the transport sector and in heat and power production, ACES2030
- Thermochemical HYDROgen production in a SOLar structured reactor: facing the challenges and beyond, HYDROSOL-BEYOND
- Promoting solar thermal hydrogen production technology through the development and validation of new materials for ceramic solar receivers with improved durability and added ferrites (HIDROFERR).
- A Lunar CHEMical In-Situ recource utilization Test plant. ALCHEMIST Phase A, ALPHA.

8 Solar Thermal Applications Unit

Introduction

The Solar Thermal Applications Unit (USTA) is devoted to the development and evaluation of solar thermal technology applications in industrial processes, including desalination and brine concentration. The main objective is to generate new scientific and technological knowledge in the field of thermal applications of solar energy, seeking approaches that take into account circular economy and the water-energy-food nexus.

Main current research lines are the following:

- Application of solar thermal energy to large capacity distillation processes, with special emphasis on multi-effect distillation (LT-MED, TVC-MED, ABS-MED).
- Application of solar thermal energy to small capacity distillation processes, with special emphasis on membrane distillation (MD) and forward osmosis (FO).
- Solar thermal plants for cogeneration of water and electricity (CSP+D).
- Application of solar thermal energy to separation processes for brine concentration and treatment of industrial effluents.
- Dynamic modelling, process optimization and advanced control strategies in solar thermal applications.
- Application of heat pumps to solar thermal energy processes.

During 2022, the Unit has engaged in two new European projects, leading CIEMAT's participation (SOL2H2O and MELODIZER). In both cases, the contribution of the team is focused on MD. A National project on hybrid cooling technologies for solar thermal applications (SOLHYCOOL) and another for improving communication and dissemination on solar energy technologies (SOL-PRÉNDETE) were also initiated, besides continuing with the participation in other three EU projects as IP (INDIA_H2O, WATER MINING and INTELWATT) and finalising another two (projects SOLWARIS and EERES4WATER). In addition, a new PhD started in 2022, focused on dynamic operation of solar-powered MD for desalination and brine concentration. The most relevant milestone for the Unit in 2022 was the launching of the Living Lab on Sustainable Desalination. This sets up an open innovation approach which will consolidate the collaboration of the Unit with industry and society in general, establishing tools for co-creation with relevant stakeholders in the water-energy-food nexus. The intention is that the Living Lab will become the context in which further innovation activities of solar desalination will be carried out by the Unit.

The international relevance of the activities carried out in the Unit is clearly supported by the participation in EU projects and the following positions currently held:

- Coordination of the Renewable Energy and Desalination Working Group of the Platform Water Europe.
- CIEMAT's representative in the "Modularisation" subtask of Task 64 of IEA SHC Solar Process Heat.
- CIEMAT's representative in the EERA Joint Digitalization Program for Energy.
- Spain's ExCo delegate at the IEA Technology Collaboration Programme on Heat Pumping Technologies.

List of projects the unit has been involved in

- Solving water issues for CSP plants, SOLWARIS
- Bio-Mimetic and Phyto-Technologies designed for low-cost purification and recycling of water, INDIA-H2O
- Promoting Energy-Water Nexus resource efficiency through Renewable Energy and Energy Efficiency, EERES4WATER
- Next generation water-smart management systems: large scale demonstrations for a circular economy and society, WATER-MINING
- Intelligent water treatment technologies for water preservation combined with simultaneous energy production and material recovery in energy intensive industries, INTELWATT
- European Twinning for research in Solar energy to (2) water (H_2O) production and treatment technologies, SOL2H2O
- Sustainable membrane distillation for industrial water reuse and decentralised desalination approaching zero waste, MELODIZER
- Hybrid cooling solutions for water saving in solar thermal applications, SOLHYCOOL
- SOL-préndete: Didáctica y divulgación de la energía solar térmica de concentración con nuevas tecnologías de realidad aumentada y virtual
- More efficient Heliostat Fields for Solar Tower Plants, HELIOSUN
- Soluciones termosolares para integración en procesos industriales, SOLTERMIN
- Solar facilities for the European Research Area - Third Phase, SFERA-III
- Solar Twining to Create Solar Research Twins, SOLARTWINS

Figure 8. Solar Thermal Applications Unit staff in 2023.

9 Solar Treatment of Water Unit

Introduction

The main objective of the Solar Treatment of Water Research Unit is the use of solar energy for promoting photochemical processes, mainly in water, for treatment and purification applications but also for chemical synthesis and production of photo-fuels. Our knowledge about solar photochemical systems and processes at pilot and pre-industrial scale is backed by 30 years of research activity. The Unit was pioneer in Spain and keeps a consolidated national leadership. The Unit has participated in more than 28 EU projects since 1997 mainly focused on the development of solar technologies for water treatment. The facilities are extremely well equipped and are among the best in the world in the field of advanced oxidation processes (AOPs). We are also pioneers in the use of advanced analytical and microbiological techniques for the evaluation of such processes. Formal collaborations in the academic sector include dozens of public institutions in the EU, South America, Australia and Africa. Industrial collaborations on recent projects include companies from Austria, Italy, Denmark, India, and many others in Spain.

In order to promote the higher education of young researchers in the environmental applications of AOPs, as well as to overcome national boundaries and bureaucratic barriers, a group of European scientists founded the “European PhD School on Advanced Oxidation Processes” in June 2014. Subsequently (October 18, 2018), with the aim to make the school international, Institutions from Latin America have joined it. Currently, the School includes 52 Scientific Committee members from 17 different Countries. The PSA is one of the members of this school since its creation and the Solar Treatment of Water Unit coordinates the European Branch. The Summer School is among the initiatives organized for the AOP School PhD candidates but other PhD students, MSc students, post-doctoral researchers and professionals are also welcome.

The high international relevance of the activities carried out by the Solar Treatment of Water Unit is demonstrated by its active collaboration with a high number of international institutions and companies as well as their participation in different specialized forums and committees: Leader of subtask B Solar water decontamination and disinfection systems in task 62 ”Solar Energy in industrial water and wastewater management” from the International Energy Agency; members of the core-group of the Zero Pollution and Water security action groups in the Water Europe Platform, etc.

The research activities already consolidated by this unit are the following, cross-linked with the projects and networks summarised below:

- Solar photocatalytic and photochemical processes as tertiary treatment for the removal of pollutants of emerging concern and microorganisms, related with AQUACYCLE (CBC ENI MED), PANIWATER (H2020-India), NAVIA, DIGIT4WATER and MODITRAGUA projects and AQUALITY Marie Skłodowska-Curie Action.
- Solar photochemical processes for the remediation of industrial wastewaters, related with CALYPSOL project and ELECTRONÍQUEL and SMALLOPS service contracts.
- Integration of Advanced Oxidation Processes with other water treatment technologies (NF/UF; Ozone, Bioprocesses, etc.), related with AQUALITY Marie Skłodowska-Curie Action, PANI-WATER, CALYPSOL and AQUAENGRI projects.
- Evaluating photocatalytic efficiency of new materials under solar light in pilot reactors, related with CALYPSOL and NAVIA projects and SMALLOPS service contract.

- Photocatalytic and photochemical processes for water disinfection in different scenarios related with ENERGICA project (Green Deal).
- Pilot solar photo-reactors for production of hydrogen and other photo-fuels, related with SolarFuture and SOLCHEM5.0 projects.

List of projects the unit has been involved in

- Interdisciplinar cross-sectoral approach to effectively address the removal of contaminants of emerging concern from water, AQUALITY
- Photo-irradiation and Adsorption based Novel Innovations for Water-treatment, PANIWATER
- Advanced and hybridized technologies addressing recalcitrant pollutants, micropollutants, reusing and revalorization in different wastewater, including technological and economical approaches, CALYPSOL
- Towards increasing the sustainable treatment and reuse of wastewater in the Mediterranean Region, AQUACYCLE
- Urban wastewater reclamation by Novel mAterials and adVanced solar technologies: assessment of new treatment quAlity Indicators, NAVIA
- Solar catalysis for a renewable energy future, SOLFUTURE
- ENERGy access and green transition collaboratively demonstrated in urban and rural areas in AfrICA, ENERGICA.
- Solar facilities for the European Research Area - Third Phase, SFERA-III
- Solar Twining to Create Solar Research Twins, SOLARTWIN
- Revalorization of acids and heavy metals in waste streams from surface treatments with membrane technologies, ELECTRONÍQUEL.
- Revalorización de diferentes aguas residuales mediante tecnologías que permitan mejorar el nexo agua-energía renovable-alimentos, AQUAENGRI.
- Hacia la mejora de la Resiliencia del Ciclo Urbano del Agua: Evaluación de tecnologías solares de regeneración de aguas con especial énfasis en la eliminación de subproductos de desinfección, bacterias y genes resistentes a antibióticos, DIGIT4WATER.
- Towards Digital Transition in Solar Chemistry, SolChem5.0.
- Monitorización y diagnóstico de la potabilización, depuración y regeneración de aguas urbanas en comarcas con estrés hídrico y desarrollo de tratamientos sostenibles alternativos a la cloración, MODITRAGUA.

Figure 9. Solar Treatment of Water Unit staff in 2022.

10 Projects

Standardization activities at Spanish and international level, Technical Committees *IEC/TC117* and *CTN-UNE 224*

Participants: ABENGOA, AENOR, AICIA, CENER, CIEMAT, PROTERMOSOLAR, SCHOTT Solar, SENER, TECNALIA, TEKNIKER; DLR, Fraunhofer, CEA, ENE, IEECAS, LNEG

Contact: Eduardo Zarza Moya, eduardo.zarza@psa.es

Funding agency: CIEMAT

Background: Since Concentrating Solar Thermal (CST) systems are a relatively young technology, the CST sector is still experiencing a lack of standards. This lack of standards is a barrier for the development of the technology and the evaluation and qualification of components. In spite of the several standards developed during the last years, there is still a significant lack of standards. Development of international standards for the CST sector has been undertaken within the technical committee IEC/TC-117.

Objectives: The scope of the international committee IEC/TC-117 implemented within the umbrella of the International Electrotechnical Commission, and the Spanish committee CTN-UNE 224 implemented within the UNE standardization body is the development of standards for the Concentrating Solar Thermal (CST) sector by putting together the experience of R+D centres, Industries, Engineering companies, components manufacturers and promoters.

Achievements in 2022: PSA Units of Line-focus Concentrating Solar Thermal (LFCST) technologies, Point-focus Concentrating Solar Thermal (PFCST) technologies, Materials for Concentrating Solar Thermal technologies (UMAT) and Thermal Energy Storage (TES) have kept on participating in standardization activities at both international and national levels in 2022. This contribution has been made under the umbrella of the international standardization committee IEC/TC-117 and the Spanish UNE committee CTN-UNE 224.

At a Spanish level, the PSA unit of LFCST technologies has coordinated and participated in the elaboration of the new UNE standard for *Criterios de diseño, instalación y verificación de las prestaciones de las juntas cinemáticas en las centrales termosolares con tecnología de captadores cilindroparabólicos*, (Design, installation and qualification criteria for rotation and expansion assemblies in solar thermal power plants with parabolic trough collectors), while the TES unit has continued its participation in the working group related to a new standard for *Sistemas de almacenamiento térmico directo*.

At an international level, a member of the LFCST technologies unit (Mrs. Lourdes Gonzalez) has been the Secretary of the technical committee IEC/TC-117 in 2022 and this PSA unit has also participated in the following IEC/TC117 project teams, together with the PFCST technologies unit, the UMAT unit and TES unit:

- MT 1 - *Terminology* (Convenor: Lourdes González Martínez, LFCST)
- PT 62862-1-4 ED1 Solar Thermal electric plant - Part 1-4: *Thermal insulation for solar thermal electric plants.*

- PT 62862-1-5 ED1 Solar thermal electric plant - Part 1-5: *Performance code test for solar thermal electric plants*.PT 62862-1-6 ED1 Solar thermal electric plants - Part 1-6: *Silicone-based heat transfer fluids for the use in line focusing CSP applications*.
- PT 62862-3-1:2022 Solar thermal electric plants – Part 3-1: G*eneral requirements for the design of parabolic trough solar thermal electric plants*, issued in 2022.
- PT 62862-3-4 ED1 Solar thermal electric plant - Part 3-4: *Code of solar field performance test for parabolic trough solar thermal power plant.*
- PT 62862-3-5 ED1 Solar thermal electric plants – Part 3-5: *Laboratory reflectance measurement of solar reflectors*. (Project leader: Aránzazu Fernandez García, UMAT)
- PT 62862-3-6 ED1 Solar thermal electric plants – Part 3-6: *Durability of silvered-glass reflectors - Laboratory test methods and assessment*.
- PT 62862-4-1: 2022 Solar thermal electric plants – Part 4-1: *General requirements for the design of solar power tower plants,* issued in 2022.
- PT 62862-4-2 ED1 Solar thermal electric plants – Part 4-2: *Heliostat field control system*
- PT 62862-5-2 ED1 *General requirements and test methods for large-size linear Fresnel collectors*, issued in 2022.

Implementation of the Initiative for Global Leadership in Solar Thermal Electricity, HORIZON-STE

Participants: ESTELA, CIEMAT, ENEA, DLR, METU.

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Funding agency: European Commission, H2020-LC-SC3-2018-Joint-Actions-2

Background: This project is a coordination and support action to provide support to the realisation of the Implementation Plan of the SET-Plan for CSP. The origin of this project was the need to propose solutions and pathways to overcome the essential shortcomings of the current national strategies related to CSP/STE that are: a) for the industry: the legal framework conditions for the procurement of manageable RES; and b) for the R&I sector: entering in working relations with national funding agencies with the objective of increasing the public funding to support the development of the R&I projects already prioritized by the European CSP/STE stakeholders according to their expected impact on the sector.

Objectives: The assessment of the conditions required to replicate in European countries the commercial cost levels (< 10 € cents/kWh) that have already been achieved by the industry on CSP/STE world markets (financial conditions, type of auctions, the contribution of innovations delivered by R&I) and paving the way for the implementation of FOAK (*First Of A Kind)* projects as one of the objectives of the Initiative and its Implementation Plan. A final objective is the active promotion for the introduction of CSP/STE into energy strategy policies at European or national levels.

Achievements in 2022: PSA activities in 2022 were devoted to work packages (WP) 2 and 3, mainly. Within WP2, the main PSA activity was the organization of the HORIZON-STE Joint Industry and R&I National Event in Spain on June 7th. The situation of the Spanish market for CST technologies was analysed in this event by research institutions, industry, national decision makers and authorities.

In WP3, PSA was collaborating with the Spanish chair of the CSP Implementation Plan (IP) to coordinate the development of the new IP in the context of the Core Group of the IWG (Implementation Working Group). A final draft for the new IP was prepared and released in December for final comments. Another activity of PSA in WP3 was the organisation of the 2nd "International workshop and brokerage event", which took place on-line on September 20th. This European webinar was the last public event of HORIZON-STE and it had three objectives:

- to analyse the presence of concentrating solar thermal (CST) technologies in the Horizon Europe Framework Programme, discussing options to increase the funding for CST technologies within the EC framework programs, not only for electricity generation but also for process heat applications and green fuels production,
- to present the results obtained from the study performed in Task 3.2 of HORIZON-STE about possibilities to implement a European Joint Funding Programme for CST technologies, and
- to present EU-SOLARIS ERIC (a new ESFRI entity) to the CST stakeholders

Another outstanding PSA activity in 2022 was the participation in the on-line meeting organized by the Spanish CDTI (Centre for Industrial Technical Development) in March, with the IWG and the Director of the new E.U. Solar Energy Strategy. The commercial potential of CST technologies for green fuels production, process heat applications and electricity generation was presented at that meeting to the people responsible for the new European Solar Energy Strategy document, thus pointing out the high potential of CST technologies for a green energy market.

Figure 10. HORIZON-STE Joint Industry and R&I National Event in Spain on June 7th.

Solar Twining to Create Solar Research Twins, SolarTwins

Participants: METU, CIEMAT, DLR

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Julián Blanco, julian.blanco@psa.es

Funding agency: European Commission, HORIZON-2020 WIDESPREAD-03-2018 TWINNING

Background: Europe is a global leader in CST technologies but this leading position is increasingly being challenged by large investments in other countries. SolarTwins is designed to respond to this challenge to European Technological Leadership by Twinning PSA and DLR's Institute for Solar

Research to the CST research laboratory at the Center for Solar Energy Research and Applications (METU-GÜNAM-ODAK) of the Middle East Technical University (METU) at Ankara (Turkey). SOLAR TWINS started in January 2020 and will have a final duration of 42 months.

Objectives: 1) Build-on and strengthen METU-GÜNAM's synergistic integration into existing EU CST and solar water treatment and desalination R&I networks containing PSA and DLR; 2) Strengthen the scientific profiles of METU-GÜNAM and its researchers; 3) Train a large, diverse and promising pool of METU Early Stage Researchers; 4) Formulate joint research lines (JRL) and look for opportunities to increase research funds to all partners; and 5) Disseminate and promote CST, water treatment and desalination technologies in Turkey. The project name *SolarTwins* reflects the formulation and execution of Individual Twinning in which an expert from PSA or DLR is Twinned to a researcher at METU-GÜNAM.

Achievements in 2022: During the year 2022, an Early Stage Researcher (Eylül Gedik), Dr. Zohre Kurt and Prof. Derek Baker stayed at the PSA to continue the research work on the integration of concentrating solar thermal energy in desalination processes such as reverse osmosis and multi-effect distillation. The first result of this collaboration has been a paper presented as a poster at the SolarPACES 2022 congress, as well as another paper on life cycle analysis of CSP+MED systems submitted to a JCR journal and currently under review. Regarding the collaboration with the Solar Treatment of Water Unit, the collaboration with Eylül Gedik and Prof. Derek Baker on combination of PV with wastewater treatment plants for water recovery has continued. In addition, collaboration with Dr. Zohre Kurt in the frame of UF and NF photocatalytic membranes for wastewater treatment has also been initiated. Finally, a new collaboration has also began thanks to the short stay of Prof. Burcu Akata Kurç and Dra. Pelin Paşabeyoğlu in the topic of new photocatalytic materials for wastewater treatment and elimination of microcontaminants contained in urban wastewater. Moreover, the PSA researchers Dr. Diego Alarcón and Dr. Isabel Oller participated as speakers in the summer school of SolarTWINS entitled "Solar water desalination and treatment technologies", which was held at the campus of METU in Ankara from August 30th to September 1st. During this course, Dr. Diego Alarcón introduced the basics of desalination, as well as a detailed review of thermal desalination processes, and the possibilities of integrating solar energy into these processes, for both desalination and cogeneration (i.e. joint production of electricity and desalinated water). On the other hand, Dr. Isabel Oller explained the bases of decontamination and disinfection technologies (focusing in solar photocatalytic processes) as well as of photo-reactors design and improvement and several examples on real cases applications of such technologies.

The Materials for CST Technologies Unit has also participated in this project in the field of solar reflectors. During 2022, the durability test campaign of the solar reflectors supplied by METU was completely finished by DLR and CIEMAT at the OPAC facility. Very promising results were achieved and a close cooperation between the three institutions was initiated. In addition, two Early Stage Researchers from METU involved in solar reflectors spent one week in July 2022 at PSA to visit our facilities devoted to this topic and to meet CIEMAT and DLR researchers working on these activities.

Solar Facilities for the European Research Area - Third Phase, SFERA-III

Participants: CIEMAT (Spain), CNRS (France), ENEA (Italy), DLR (Germany), CEA (France), UEVORA (Portugal), ETHZ (Switzerland), IMDEA (Spain), CYI (Cyprus), Fraunhofer (Germany), LNEG (Portugal), METU (Turkey), UAL (Spain), EURO (France), ESTELA (Belgium).

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Funding agency: European Commission, H2020-INFRAIA-2018-1.

Background: Research infrastructures (RIs) are facilities, resources and services that are used by the research communities to conduct research and foster innovation in their fields. They play an increasing role in the advancement of knowledge and technology and their exploitation. By offering high quality research services to users from different countries, by attracting young people to science and by networking facilities, RIs help to structure the scientific community and play a key role in the construction of an efficient research and innovative environment. Because of their ability to assemble a 'critical mass' of people, knowledge and investment, they contribute to national, regional and European economic development. RIs are also key in helping Europe lead a global movement towards open, interconnected, data-driven and computer-intensive science and engineering.

Objectives: The SFERA-III project aims to engage all major European Solar Research Institutes with relevant and recognized activities in the Concentrating Solar Thermal (CST) technology field, into an integrated structure, operating a unique set of Concentrating Solar Thermal (CST) RIs to promote innovative research, to improve services offered by CST research infrastructures and to train researchers and engineers on the CST technologies. In this project, both academia and industry users are targeted.

Achievements in 2022: During this year, CIEMAT successfully organised and coordinated several General Assembly, Management Board and Access Manager meetings in order to favourably implement the project. Also, this year, CIEMAT organised and lunched the fifth call for proposals to access the installations offered by the SFERA-III project and coordinated the evaluation of the proposals received in the fourth call, including the organisation of the User Selection Panel meeting to the discuss the scores.

In WP1, CIEMAT collaborated with DLR in the organization of the 2nd Training Course for the Industry on "Optimization of CST plant output by optical and thermal characterization and target-oriented O&M" which took place at the Plataforma Solar de Almería (PSA), Spain, from 25 to 29 April 2022.

In WP2, CIEMAT participated in the workshop (WS8) related to WP10 on pyrheliometer calibration, organized by DLR at PSA from 4 to 15 July 2022, with sensors provided by DLR, CIEMAT, CNRS and EVORA.

In WP3, CIEMAT, as leader of the task for the promotion of long-term sustainability but also as responsible of the EU-SOALRIS ERIC, has been working in collaboration with the European Strategy Forum on Research Infrastructures and the countries participating in EU-SOALRIS (Spain, France, Germany and Cyprus) to finally achieve an ERIC legal status for EU-SOALRIS on 19 October 2022. See section 11 for more details.

In the framework of the transnational access activity, CIEMAT has offered a total of 37 weeks of access to 17 users with the following distribution: 12 weeks to SOLFU, 10 weeks to MOSA, 10 weeks to SOLWATER and 5 weeks to DESAL.

The Thermal Energy Storage Unit coordinates WP6, entitled Development of Test Procedures for Materials and Components of Thermal Storage Systems. Closely linked to the ACES2030 regional programme and StoRIES EU funded project, in Task 6.2 during 2022 CIEMAT carried out the kinetic analysis of isothermal tests in oven when evaporation is one of the predominant degradation processes as it happens in some PCM like lauric, myristic, stearic or adipic acid. Two different mathematical models were used to predict the amount of PCM lost in kg per square meter of surface. These kinetic studies have demonstrated that, for the case of adipic acid, more than 100 kg of PCM/m^2

would be lost after 1 year if it kept molten at 160 °C which is only 8 °C above its melting temperature (see Figure 11). This clearly indicates that the main problem of adipic acid is that it quickly evaporates as soon as it is melted, which prevents this PCM from being used for latent storage at least in unsealed systems.

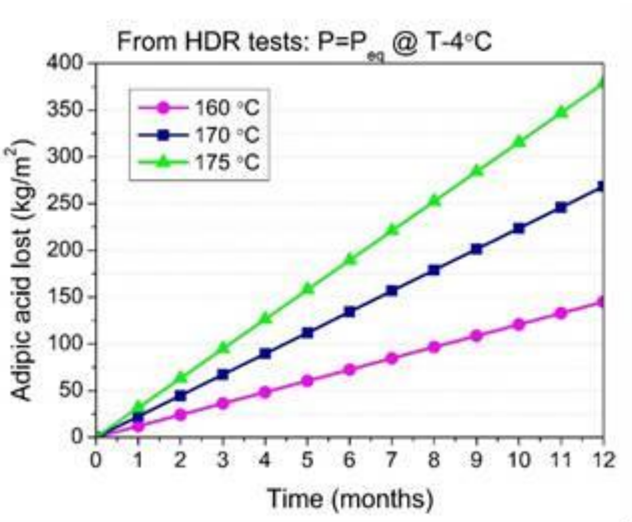

Figure 11. Prediction of mass loss of adipic acid when it is kept molten at constant temperature (Tm+8 °C+18 °C and +23 °C).

Discussions on the test procedures for prototype testing has been concluded and, in collaboration with the rest of the partners, D6.3 (Protocol for testing sensible and latent storage prototypes. Towards the Standardization of testing prototypes for storage systems) has been submitted. In collaboration with the Thermal Storage Working Group of SolarPACES Task III, which is also coordinated by Margarita Rodriguez, a Thermal Energy Storage Unit expert, discussions on testing molten salt equipment and components continues in Task 6.4.

In WP7, and particularly within Task 7.2, CIEMAT has collaborated with the University of Évora in the testing of a new CPC solar reactor. Experimental tests of degradation by photolysis and heterogeneous photocatalysis with titanium dioxide of four pharmaceutical compounds and phenol were carried out to test the performance of this prototype under real climatic conditions. As part of Task 7.3, CIEMAT & UAL have carried out an experimental campaign at the nanofiltration pilot plant to test a multivariable control design with decouplers aimed at maintaining permeate production under different operating conditions in municipal wastewater regeneration. They have also worked on an optimal model-free operation strategy for solar MD systems operating in batch mode. CIEMAT has developed a new guideline to evaluate the performance of MED processes, which will be validated during 2023. CIEMAT has also been involved in the implementation of a new open-source SCADA system for water-related experimental facilities. Within Task 7.4, CIEMAT has collaborated with CEA to benchmark their software developments for RO+PV and MED.

In WP8, CIEMAT is participating in tasks 8.2 and 8.3. Specifically, in Task 8.2, Tests procedures to assess the performance of materials for solar fuel production, CIEMAT contribued to the Deliverable 8.5: Testing of benchmarking techniques, where the application of the performance indicators developed in task 8.2 for solar thermochemical reactors operated in RS tower are outlined. In Task 8.3, Dynamic Control and Automation of Solar Fuel Reactors, CIEMAT has participated in the elaboration of Deliverable 8.4 "Implementation of reactor and systems control tool". The goal was to provide detailed examples of the performance of control strategies to track set point changes in a proposed water-splitting reactor alternating between two temperatures. Recently, a modification of the control scheme based on development of a feedback linearization (FL) technique is carried out. The output of the FL strategy is the power setpoint required on the reactor to achieve the setpoint temperature. FL control is combined with an optimization problem based on genetic algorithms (GA) to find the best combination of heliostats that must be focused on the reactor. This task is carried out in collaboration with the Solar Thermal Applications Unit.

In this workpackage, CIEMAT also explored the performance of secondary optics manufactured in the PSA and installed in the 100 kW cavity reactor concept located at CRS. The goal of this study was to find out which is the most suitable geometry in terms of getting flux homogeneity as well as to determine which configuration provides the higher amount of power entering the cavity. In WP9, within task 9.2 "Improving the infrared temperature measurements thanks to better assessment of the emittance and its evolution", CIEMAT has participated in the round robin comparison of emissivity measurements of receiver materials for CST, together with CNRS, DLR, CEA and LNEG. Within task 9.3 "Evaluation of Airbone IR measurements", the Line-Focus Solar Thermal Technologies unit has performed a second test campaign to complete the data sets to apply the Surface Temperature Method to determine the existence of vacuum or the total or partial loss of vacuum in the annulus of the receiver tubes by measuring the temperature of the glass envelope using IR cameras. The study on how meteorological variables influence IR measurements was completed and a scientific paper was presented and will be published in 2023. In addition, CIEMAT and DLR jointly conducted indoor and outdoor IR camera inter-comparison tests in the laboratory and at the KONTAS test facility.

In WP10, specifically in Task 10.1 "Improved sensor monitoring/calibration and measurement accuracy of IR laboratory test beds", the Line-Focus Solar Thermal Technologies unit has completed a laboratory test campaign to calibrate a first prototype manufactured from CIEMAT's patented device to measure the forces and moments applied on parabolic trough rotating and expanding assemblies. The system and calibration results were presented at the SolarPACES 2022 conference (see 16). In addition, in this task 10.1 we have participated in a new round robin test to increase the quality of service of the test benches for PTR heat loss measurement. At the end of the year, CIEMAT received an HCE unit, whose heat losses were measured in the HEATREC test bench, both in laboratory atmosphere conditions and inside a vacuum chamber, applying in both cases the test method defined in the technical specification IEC TS 62862-3-3-3. Additionally, the Materials for Concentrating Solar Thermal Technologies Unit has participated during 2022 in Task 10.1.A activities. The round robin tests for artificially soiled solar mirrors conducted in 2021 were further evaluated and discussed within the partners of this task. The linear transfer functions for the handheld reflectometers as well as the participating TRaCs Device were identified for two types of sand (Almeria and Negev) and for the soiling coupons, dedicated for calibration and reproducible intercomparison of the devices. The focus was given to an improved understanding of transfer functions and influence of soiling on application and measurement. The behaviour of the soiling coupons (developed by DLR and CIEMAT) was further analysed with respect to spectrally resolved hemispherical and specular reflectance. It was agreed that the sand blasted samples showed the most robust results in the round robin tests, and showed generally a more similar behaviour to solar mirrors subject to soiling.

It is also worth mentioning the coordination of WP11, which is devoted to the detailed design of the e-infrastructure that will connect the main European R+D centres involved in concentrating solar technologies. During the year, CIEMAT has been working with the company TECNATOM on the detailed design and specifications of the e-infrastructure as well as on the budget required to implement it in the future.

POwering SYstem flexibiliTY in the Future through Renewable Energy Sources, POSYTYF

Participants: ENEDIS, CIEMAT, IBERDROLA, Dowel, RTE, ETHZ, UPC, ECN, Comillas-IIT, HTW, Bachmann.

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Funding agency: European Commission, EU - H2020 - LC-SC3-RES-16-2019

Background: The Energy Union framework strategy aims to make the EU "the world leader in renewable energy". A high share of variable renewable generation will pose new challenges for the integration of the energy produced in an efficient and cost-effective way, for the operation of EU power systems. A key question is whether there will be enough flexibility in the power system.

Objectives: POSYTYF project intends to support the further integration of Renewable Energy Sources (RES) into the power system by developing the Dynamic Virtual Power Plant concept (DVPP). This DVPP aims to aggregate in a portfolio some renewable sources of both dispatchable and non-dispatchable natures, thus enabling an optimal internal redispatch of resources.

Achievements in 2022: This project started in June 2020 and CIEMAT is contributing to work packages WP1, WP2 and WP5. Our contribution to WP1 ended at the beginning of 2021. In WP2, CIEMAT was involved in the development of simulation models of concentrating solar thermal power plants for grid integration studies. A simplified model of Solar Thermal Electricity (STE) plants that can be easily integrated with power generation models was built and tested in MATLAB®, including its validation with real data from commercial STE plants. The description, validation and implementation of the model was included in the Internal Report "Simplified Model of a Solar Thermal Electricity Plant" and it was also presented at the 28th SolarPACES Conference (26-30 September 2022. Albuquerque, New Mexico, USA) under the title: Modeling of Solar Thermal Electricity Plants in the POSYTYF Research Project for an Extensive Integration of Renewable Energy Sources authored by L. González, M. Biencinto, L. Valenzuela, L. Arribas, J. Polo.

Finally, in WP5 CIEMAT collaborated on the generation of renewable production data sets of STE plants for the operation and management of VPPs (Virtual Power Plants). In addition, CIEMAT participated in the improvement of simulation models of STE plants for the economic optimization of DVPPs (Dynamic Virtual Power Plants), sharing information of operation parameters, response times and typical features of STE plants. Besides, a novel and simple method to generate random solar radiation profiles oriented to the uncertainty assessment of STE production forecasting was also developed within WP5. This work was published in the Journal of Cleaner Production 379 (2022) 134821 under the title: Using time-windowed solar radiation profiles to assess the daily uncertainty of solar thermal electricity production forecasts, authored by Mario Biencinto, Lourdes González and Loreto Valenzuela.

SMALL-SIZED PTCS PRESSURIZED WATER TEST LOOP - LAVEC

Participants: CIEMAT

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Funding agency: Ministry of Science and Innovation within the Special State Fund for Dynamization of Economy and Employment, co-financed by Programa Operativo FEDER Plurirregional de España (POPE) 2014-2020.

Background: The use of solar energy for the supply of thermal energy to industrial processes is a market with a high growth expectation. However, there is a lack of test facilities suitable for qualifying and evaluating line-focus solar collector designs for this type of solar energy application. The lack of this type of facility is a barrier for the commercial development of these solar thermal systems.

Objectives: Taking into consideration the current lack of experimental facilities for evaluating and qualifying small line-focus solar collectors, it was decided to design and build a new PSA test facility, suitable for the testing of medium temperature (100 - 250°C) solar thermal collectors. Any type of line-focus tracking solar collector can be tested in this facility, using pressurized liquid water as heat transfer fluid. The design of this facility is based on the previous project CAPSOL (already out of work), that was used for testing prototypes of small-sized parabolic trough collectors (PTC) using pressurized hot water up to 220°C. Additionally, this facility will fulfil the current standards for solar thermal collectors testing: ASTM E905-87:2013, SRCC 600 2014-17:2015 and ISO 9806:2017.

Achievements in 2022: The initial piping layout was reviewed and a stress analysis was carried out early in 2022. Some technical improvements were thus introduced in the initial design made in 2021. Afterwards, the hydraulic circuit, water storage tank, electrical heater and cooler and the feed pump were installed at PSA. A pressure test of the complete hydraulic circuit at 60 bar was successfully performed in September. The technical specifications for instrumentation and control systems were elaborated and the instrumentation and control devices were installed in October-November 2022. A first design of the SCADA (Supervisory Control and Data Acquisition*)* system for LAVEC was made in December. Figure 12 shows the operator interface of the SCADA system designed in 2022. Late in 2022, the prototype of innovative linear Fresnel solar collector (iLFC) developed by CIEMAT-PSA in collaboration with the University of Antofagasta (Chile) within the framework of the project SOLTERMIN, was connected to LAVEC for evaluation.

Due to time constraints, the thermal insulation of LAVEC could not be installed in 2022 and it will be installed in 2023 to start up and put this new PSA facility into operation. For further information about the technical parameters of LAVEC, please see the section of this annual report devoted to PSA Facilities.

Figure 12. View of the LAVEC test facility in December 2022.

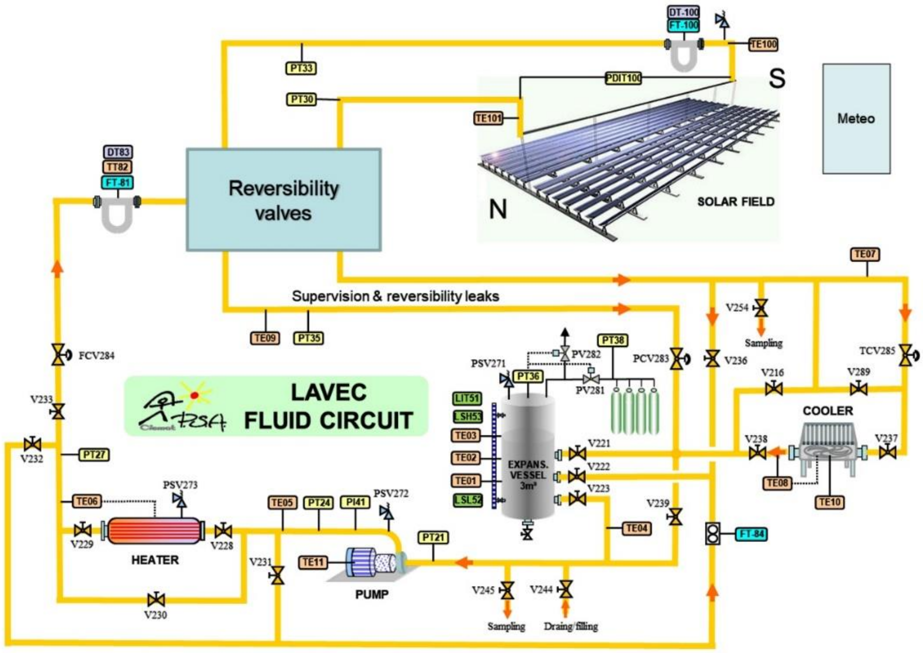

Figure 13. Simplified scheme of LAVEC.

Soluciones termosolares para integración en procesos industriales, SOLTERMIN

Participants: CIEMAT

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Funding agency: MINECO -Retos Investigación 2017: Proyectos I+D+i (Ref. ENE2017-83973-R) (Jan. 2018 – Jun. 2022)

Background: Commercial deployment of concentrating solar thermal (CST) technologies has grown significantly, with about 5GWe of installed capacity worldwide for electricity generation. However, the commercial use of concentrated solar thermal energy is still very limited, despite the fact that more than 66 % of total energy consumption in the industrial sector is dedicated to industrial heat processes.

Objectives: The project SOLTERMIN aims to advance in the development of new components and solutions to facilitate the integration of concentrated solar thermal technologies as thermal energy provider in industrial processes, with the following objectives:

Development of an innovative linear Fresnel solar collector (iLFC) for its integration in industries, including the development of a lightweight and optimized primary concentrator design to reduce optical losses and the development of an absorber coating valid up to 400 °C and stable in air.

Research on solar components for tower systems devoted to industrial process applications, including innovative and optimized heliostat designs and volumetric air receivers.

Study of the durability and reliability of solar reflectors installed in industrial environments.

Integration of linear Fresnel solar systems in different industrial processes: a) from a food and drink industry; and b) multi-effect distillation (MED) plant with steam ejectors. And integration of a solar tower system coupled to a Brayton cycle and a MED plant.

Achievements in 2022: During this last year of the project, the construction of the iLFC and its optical qualification was finished. The detailed engineering and manufacturing of the solar receiver was completed at the PSA workshop and its installation on the first iLFC prototype was done in summer (see Fig. 95). Before the installation of the receiver, a new flux measurement test campaign was executed, once the collector tracking system was running in completely automatic mode and the mirrors facets were re-aligned (see Fig. 96). Results of this flux measurement test campaign and of the incidence angle modifier analysis performed by ray-tracing were presented in the conference CIES 2022 (see publications). With regards the heliostat designs, for the development of a heliostat with self-aligned optics, the CAD design of all the system components (support structure, reflective facets, and couplings) has been completed, as well as a calculation of structural deformations, by means of CFD by self-weight and against the action of the wind. The heliostat structure was manufactured and assembled, including a protocol for checking the optical quality of the parts. In addition, durability tests have been carried out on a new reflector, also designed by CIEMAT. Results of these progresses on the heliostat with self-aligned optics were also presented in the conference SolarPACES 2022 (see publications). Rest of scientific activities scheduled the project had had already finished previously and were reported in Annual Report 2021.

(a) (b)

Figure 14. View of the iLFC cavity receiver during the manufacturing process in the PSA workshop (a) and during its installation and alignment in the iLFC prototype installed at PSA (b).

Figure 15. View of the iLFC prototype of the SOLTERMIN project during flux measurement test.

Silicone Based HTF in Parabolic Trough Applications – Preparation of an international standard, Si-HTF Standard

Participants: DLR, CIEMAT, MASEN, IEECAS, NREL, Industrial partners.

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Funding agency: SolarPACES (International Energy Agency) (Mar 2021 - Oct 2022)

Background: Recent improvements in silicone-based heat transfer fluids, in terms of increasing maximum operation temperatures and reducing cost, have originated the development of new projects that are demonstrating the applicability of said fluids and the economic viability in parabolic trough collectors (PTC) applications.

Objectives: After the formation of an international expert work group that prepared a SolarPACES guideline document about the use of silicone based HTF in parabolic trough applications, which is available at the SolarPACES website, this new project aims to compile an international standard to be submitted to the IEC TC 117 that records the results of the guideline work. The project has a duration of 18 months and has the following objectives:

- Continuation of the international expert work group that successfully elaborated the guideline for the admission of SHTF in parabolic trough collector applications.
- Incorporation of international feedback concerning the guideline document published through SolarPACES.
- Compilation of an international standard including test methods for the qualification and use of silicone based

Achievements in 2022: The project started in March 2021 with the preparation meetings to launch the project proposal of the standard draft to be submitted to the International Standardization Committee IEC TC 117:Solar Thermal Power Plants. The IEC project proposal was submitted with the number 117/126/NP and with title "Silicone-based heat transfer fluids for the use in line focusing CSP Applications". The positive voting to prepare the official standard was communicated in May 2021, and a draft for the standard was completed during the first quarter of 2022 with the code IEC CD 62862-1-6. The structure of the standard is similar to the one already published in Spain for HTFs currently used in Spanish solar power plants with parabolic troughs (UNE 206015), in which preparation CIEMAT was also involved. The draft of the standard IEC CD 62862-1- for SHTFs has been circulated by IEC during 2022 for collecting comments from the different worlwide national standardization committees. It is expected to complete the revision of comments received and close the final text of the norm during the first semester of 2023. Status can be tracked in this link.

HELISOL®XLP evaluation under real solar conditions, SING

Participants: DLR (coordinator), CIEMAT, Wacker Chemie AG, TSK Flagsol Engineering GmbH, Senior Flexonics GmbH, TÜV NORD SysTec GmbH & Co. KG, STEAG Energy Services GmbH, Rioglass Solar, S.A. Flucon Fluid Control GmbH, Dickowpumpen GmbH, RWE Renewables GmbH, Heat 11 GmbH & Co. KG

Contacts: Loreto Valenzuela, loreto.valenzuela@psa.es

Funding agencies: BMWi - Federal Ministry for Economic Affairs and Energy (Sept. 2020-August 2022).

Background: Silicone based heat transfer fluids (I-SHTF) have been used in the past as heat transfer fluids in medium scale installations such as PTC test loops e.g., at PSA (Spain), NREL (USA) and elsewhere (DOW, Syltherm 800®). Si-HTFs are pumpable below 0 °C, environmental-friendly, low in hydrogen formation, almost odourless and very low in acute toxicity. New silicone oils are being developed by other companies, as well as an international standard is being prepared to define the characterization procedure for this type of oils. The development, testing and demonstration of the reliability, performance and competitiveness of new Si-HTFs are of great interest of the CSP sector.

Objectives: The SING project is the continuation of the SIMON and SITEF projects (2016 and 2020) and has the objective to accelerate the market introduction of a new HELISOL® product: HELISOL® XLP with improved properties and associated parabolic troughs solar field's components (REPAs and receiver tubes) at temperatures up to 450°C. Such operation temperatures are beyond state of the art in PTC power plants and increase the overall power plant efficiency. This innovate project is based on a German-Spanish cooperation making use of the so called PROMETEO and REPA test facilities located at PSA.

Achievements in 2022: Activities performed by CIEMAT in the SING Project during 2022 were split in two main areas: a) providing technical support to DLR (project coordinator) and the partners in the preparation for the sensor bypass installation at the collector field outlet, and b) conducting PROMETEO plant operation and maintenance, civil work and piping loop modification activities. This involved operating the PROMETEO plant for Helisol XLP aging until May, supervising the installation of a new magnetic-drive pump, as well as monitoring and analyzing alternative options when the new magnetic-drive pump failed in summer. It was found out that the existence of small iron particles inside the piping is a major issue when magnetic-drive pumps are used, because these particles are attracted by the magnetic drive and their accumulation may block and damage the pump. Options to remove small iron particles from the oil piping were investigated in collaboration with DLR and the manufacturer of the new magnetic-drive pump. In term of Helisol aging, CIEMAT successfully achieved 300 hours out of the planned 480 at 435 °C.

Figure 16. PROMETEO test facility used at PSA for HELOSOL XLP aging.

Rotation and Expansion Performing Assemblies (REPA) Guideline

Participants: DLR (coordinator), CIEMAT, Senior Flexonics GmbH

Contacts: Rafael López, rafael.lopez@psa.es

Funding agencies: BMWi - Federal Ministry for Economic Affairs and Energy (Sept. 2020-August 2022).

Background: Rotation and expansion performing assemblies (REPAs) are key elements of solar fields with parabolic trough collectors because these elements are needed to connect the receiver tubes of adjacent collectors and also the inlet and outlet of each row of collectors to the solar field piping. REPAs are used since the very beginning in commercial solar plants. However, there is no standard regulating their manufacture, testing and characterization.

Objectives: The REPA-Guideline project has been promoted by DLR and Senior Flexonics and it combines the experience of different Rotation and Expansion Performing Assembly (REPA) test rigs with diverse test procedures towards a documented uniform test cycle (to be documented in the REPA testing guideline), which will later be the basis for the preparation of an international standard. This Project is therefore assigned to the area of "pre-normative research for the preparation of a standard". This project is one of the projects performed at PSA based on a German-Spanish cooperation and it makes use of the REPA test facility located at PSA.

Achievements in 2022: In the scope of the REPA Guideline project, the PSA REPA testing facility has been operated and maintained by the CIEMAT for accelerated aging of a set of SeniorFlexonics REPA swivel joint prototype. Accelerated aging test consisted in recirculating HTF at 393°C and 35 bar through the REPAs while a continuous rotation (-23.5° to 187°) and translation (14.24° to -4.74°) movements of the traverse is performed. This test reproduces the mechanical aging of the REPAs under thermal power plant conditions of pressure and temperature, performing 10.000 cycles, that represent 25 years, by operating continuously 100 cycles/day. The fluid for this test is the most used HTF in commercial solar thermal power plants, the eutectic mixture Therminol VP1. A complete test campaign was carried out. In collaboration with DLR, other works performed in this period were: increase the reliability of the load cell sensors used to measure the torque and forces in samples under testing, design and implementation of a controller for a hydraulic actuator in an oscillating system, analysis of mechanically induced noise on flexible pipe connectors for parabolic trough solar collectors, implementation of leak measurements in a test bench for flexible pipe connectors.

Figure 17. View of the REPA test facility during operation at PSA.

High performance parabolic trough collector and innovative silicone fluid for CSP power plants, Si-CO

Participants: Acciona Industrial (coordinator), DLR, CIEMAT, Wacker Chemie AG, Rioglass Solar Systems LTD., Thermal Power Engineering S.L., Rioglass Solar SCH S.L., Senior Flexonics GmbH

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Funding agencies: CSP ERANET Co-fund Call - T3. Parabolic Trough with Silicon Oil. Transnational Call CSP 4.3 2016; MICINN Proyectos I+D+i Programación Conjunta Internacional, Convocatoria 2020-2. Referencia PCI2020-120704-2 (Apr 2021-Apr 2024)

Background: Silicone based heat transfer fluids (Si-HTF) have been used in the past as heat transfer fluids in medium scale installations such as PTC test loops e.g., at PSA (Spain), NREL (USA) and elsewhere (DOW, Syltherm 800®). SHTFs are pumpable below 0 °C, environmental-friendly, low in hydrogen formation, almost odourless and low in toxicity. Until now, such fluids are not used in large-scale commercial CSP power plants because available SHTFs have been far more expensive than the widely used eutectic mixture of diphenyl oxide and biphenyl (DPO/BP). However, the development of new formulations of SHTFs open the door to their wide application in parabolic trough applications. Such new application e.g., in future power plants, to make them more competitive, will also require new designs of parabolic troughs optimized to work with the new operating conditions allowed for new SHTFs.

Objectives: The Si-CO project aims to techno-economically demonstrate a new optimized and large-scale parabolic trough collector (Si-PTC) design that operates using HELISOL®XLP at 430 °C, a Si-HTF. The demonstration will take place at Plataforma Solar de Almería, mainly at the so-called PTTL test facility.

Achievements in 2022: In this project, CIEMAT is participating mainly in the WP5 "Commissioning and qualification of the new Si-PTC and key components" and in WP6 "Si-PTC operation with HELISOL®XLP". During 2022, CIEMAT has continued the preparatory works in the Balance of Plant (BOP) of the PTTL test facility, where the demonstration will take place. 20 IBCs of 900l of HELISOL® XLP were delivered by Wacker and the PTTL BOP filled with the new heat transfer fluid and new functional tests of all the equipment, i.e. pump, gas-heater, air cooler, automatic valves, instrumentation, etc., have been executed this year. Other technical activities done by CIEMAT during this year have been: (a) elaboration of a wind rose with datasets from the last five years, needed by TEWER for the structural design of the new parabolic trough collector; (b) calculation of heat transfer coefficients and film temperature in the solar receivers with the new HTF, which are data needed for the operational conditions definition; (c) definition of input/output signals and requirements for the communications with the LOC of the new collector designed. The construction, commissioning and qualification phase of the new Si-PTC is scheduled for 2023. CIEMAT and DLR also agreed on the collaboration to supply HCEs units to DLR to be contaminated with H_2. In 2022, the heat losses of a set of receiver tubes were measured by CIEMAT at the receiver tubes lab at PSA. This set of tubes was sent to DLR headquarters in Köln for its adaptation to be contaminated with H_2. CIEMAT will repeat heat loss measurements before and after the continuous field testing planned at the KONTAS test facility of the PSA.

(a)

(b)

Figure 18. Aerial views of the PTTL pilot plant at the Plataforma Solar de Almería: (top) in red the area where the new large aperture parabolic trough prototype will be installed and (b) the BOP where equipment upgrades and the new Si-HTF (HELISOL® XLP) conditioning have already been carried out (Latitude 37°05′45″N, Longitude 2°21′12″W).

Development of Innovative Concept for a Thermo Solar Parabolic-Through Power Plant with Molten Salts in Fixed Tube and Thermocline-Type Heat Storage Coupled with Green Hydrogen Generation System, NEOSOLAR

Participants: Intecsa Ingenieria Industrial S.A. (Coordinator), Esasolar Energy System S.L., Tewer Engineering S.L., CIEMAT, CENER

Contacts: Loreto Valenzuela, loreto.valenzuela@psa.es

Funding agencies: CDTI (Programa Misiones, Ciencia e Innovación, 2021). Ref. MIG-20211012 (Oct. 2021-Dec. 2024)

Background: The achievement of the objective defined by the European Commission for the reduction of greenhouse gases emissions (55 % with regard to the emissions in 1990) demands a huge effort from all the member countries in order to decarbonize their energy sector by means of a massive use of renewable energy sources in the domestic, transport and industrial sectors. The use of cost-effective energy storage systems becomes more and more important as the implementation of non-dispatchable renewable energies technologies increases. At the same time, the production of green hydrogen is considered a very suitable way to couple the electricity sector and the gas sector with a twofold use: to provide a flexible energy storage option and to use the curtailments of renewable electricity plants. Therefore, developing plants to produce renewable hydrogen and at the same time supply electricity at a competitive cost, is of high interest nowadays.

Objectives: NEOSOLAR is aimed at developing an innovative renewable energy system based on a solar thermal power plant with cheaper and more efficient parabolic-trough collectors using molten salts as working fluid and an electrolyser plant that altogether will reduce the curtailments that would otherwise be wasted and are affecting negatively to the profitability of renewable electricity plants. The innovative plant concept pursued in NEOSOLAR will deliver cheaper solar thermal electricity and competitive green hydrogen that could be used as both energy storage medium and energy vector.

Achievements in 2022: The PSA R&D Unit of Line-focus Concentrating Solar Thermal Technologies has participated in Activity 1 of NEOSOLAR in 2022. This Activity is devoted to the development of an innovative parabolic-trough collector. PSA has collaborated with INTECSA and ESASOLAR in a review of the state-of-the-art, related to previous studies about fixed-tube designs mainly. PSA has also contributed to the design of the new collector, providing comments to the several technical documents prepared by INTECSA and ESASOLAR related to the design parameters for the new solar collector.

PSA has also released several documents related to the test procedure that will be applied for the evaluation of the prototype of the new collector, and the required interface with the current SCADA system of the test facility where the prototype will be installed for operation under solar conditions. Finally, the so-called HTF Test Loop of the PSA (the test facility where the prototype will be installed and evaluated) has been improved in 2022, with the installation of a new oil feed pump and a bigger oil expansion and storage tank. Additionally, some equipment that will be required to perform the planned test campaign was purchased in 2022.

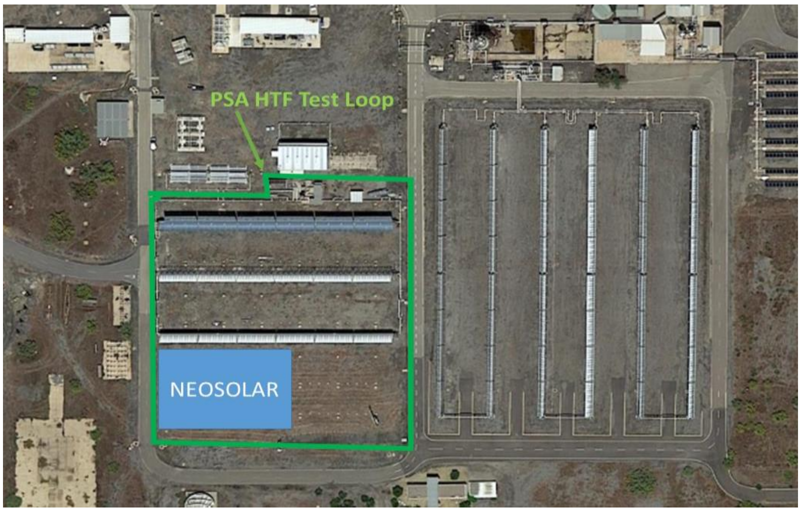

Figure 19. Aerial view of the PSA HTF Test Loop and planned location for NEOSOLAR

Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower systems – NEXTOWER.

Participants: ENEA (coordinator), KTH, POLITO, CIEMAT, ICCRAM, UOXF, URM1, SANDVIK MT, BEWARRANT, CERTIMAC, R2M SOLUTIONS, LIQTECH, CALEF, SILTRONIX, GREEN CSP, ENGICER, UNE.

Contacts: Jesús Fernández-Reche, jesus.fernandez@psa.es
Antonio Ávila-Marín, antonio.avila@ciemat.es
Inmaculada Cañadas, i.canadas@psa.es

Funding agency: European Commission. H2020-NMBP-2016-2017. Grant Agreement number: 721045.

Background: While volumetric air CSP towers are socially and technically appealing, for their great environmental sustainability and the potential for electrical and thermal power generation, their industrial exploitation has been significantly slowed down by the materials used for the core component (i.e. the high temperature solar receiver) which is affected by limitations in maximum working temperatures and in-service overall durability, mainly due to failure by thermal cycling.

Objectives: NEXTOWER project aims at demonstrating high-performance durable materials for the next generation of concentrated solar power (CSP) air-based tower systems, making them commercially competitive in the energy market beyond 2020. NEXTOWER responds by taking a comprehensive conceptual and manufacturing approach that starts by optimizing for durability the ceramic materials to achieve 20-25 years of maintenance-free service receiver components, while increasing their operating temperature for thermodynamic efficiency at the system level and possible unprecedented applications downstream, such as the direct interfacing with a Brayton cycle or the supply of zero-emission heat for industrial/chemical processing.

Achievements in 2022: In a follow-up of the project after its conclusion, more than 100 testing hours, at temperatures up to 900 °C, have been accumulated for two of the different volumetric absorbers without any significant problems of the materials/cups. A new graduated porosity configuration (see Figure 20 below) presents very promising results in terms of durability and thermal performance.

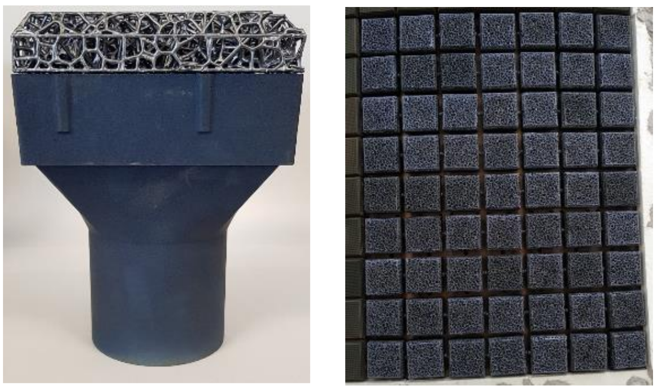

Figure 20. Gradual porosity absorber developed under the NEXTOWER project.

Wind adapted heliostat, based on field measurements in the heliostat field and validation of wind tunnel measurements – AdaptedHelio.

Participants: DLR, FRAUNHOFER, CIEMAT-PSA.

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Jesús Fernández-Reche, jesus.fernandez@psa.es

Funding agency: German Federal Ministry for Economic Affairs and Energy (BMWi, contract number 03EE5056).

Background: The cost of installing heliostat fields accounts for approximately 50 % of the total cost of a central tower solar power plant, which allows for a large margin of cost reduction. Knowing the wind intensity and direction profile in the heliostat field can help to relax the technical requirements of the heliostats installed in the heliostat field. In this way, more economical heliostats can be installed in those areas where the wind intensity allows it.

Objectives: The objective of the AdaptedHelio collaboration between DLR, Fraunhofer and CIEMAT is to determine the space-time wind profile on a semi-commercial heliostat field and to develop procedures to extend these results to heliostat fields of different types: larger and with heliostats of different sizes.

Achievements in 2022: This year marked the real start of the project. With the installation of the 2 lidars, the measurement system is finally complete. In this way, the local measurements of the 4 anemometers located in different positions of the solar field are complemented with the wind speed distribution map over the heliostat field generated by the 2 lidars. All this measurements, combined with the orientation (azimuth and elevation) of each of the 300 heliostats of the solar field, will allow modelling both, the distribution of wind speeds in the heliostat field, as well as the behaviour of the heliostats under this wind speed distribution.

Figure 21. Lidar with the CESA-I heliostat field at the foreground

Solar extinction measurements system commercialization – Ref. 8510/2018.

Participants: BCB Informática y Control S.L., Plataforma Solar de Almeria (CIEMAT-PSA).

Contact: Jesús Ballestrín, jballestrin@psa.es.

Background: CIEMAT has developed a solar extinction measurement system at PSA after years of research. This measurement system is now a reference and is demanded by companies in the concentrated solar sector.

Objectives: The main objective of the project is the commercialization of a system for measuring solar extinction developed by CIEMAT at PSA. This system allows quantifying the losses from the heliostats to the receiver placed at the top of the tower plant. In order to respond to the demand for this measurement system by companies in the concentrated solar sector, knowledge about this system have been transferred to BCB company with the consequent economic consideration to CIEMAT for each one of the installed systems.

Achievements in 2022: As a result of the technology transfer contract to the Spanish engineering company BCB, the second commercial atmospheric extinction measurement system has been implemented in a 100 MW commercial power tower plant that is using molten nitrate salts at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai (United Arab Emirates).

Solar field measurements to increase performance – LEIA.

Participants: CIEMAT (coordinator), Acciona Industrial, CSP Services, DLR, TEWER Engineering, CENER, Siemens Energy, Grupo Cerro.

Contact: Antonio Avila, antonio.avila@ciemat.es

Funding agency: CSP ERA-Net Additional Call. T5 - Improved central receiver molten salt technology. Transnational Call CSP ERA-Net COFUND 2021. MICINN Proyectos I+D+I "Programación Conjunta Internacional", Convocatoria 2022-2. Referencia PCI2022-135015-2 (Dec 2022 - Nov 2025).

Background: Central receiver systems using molten nitrate salts as heat transfer fluid are the preferred choice when the power tower technology is the CSP solution. Current commercial plants with this technology envisaged for a reduction in both operation and maintenance costs as well as the great deal of labour that some processes, such as heliostat calibration, receiver operation, solar field and whole plant control strategies, etc., require.

Objectives: The aim of the project is to contribute to the market deployment of the next generation of innovative, reliable, and smart Concentrated Solar Power (CSP) plants focusing on new control and Operation and Maintenance (O&M) solutions for the central receiver technology using molten salts, as the most promising cost-effective solution with the highest market potential. To achieve it, the LEIA project will develop and test at PSA, CENER, and the Cerro Dominador CSP plant:

Smart heliostat field control solutions to automate and improve calibration and characterization.

Smart Receiver Control solutions to measure receiver temperature, emittance and high solar irradiance distribution.

Solar Field O&M control strategies such as Automated Soiling Inspection and a Smart Energy Management system.

Achievements in 2022: The project was officially launched in December 2022. CIEMAT, as coordinator of the project, will manage WP1 "Project management and coordination", and will actively participate in WP2 "Smart heliostat field control solutions detail engineering" with the development in task 2.1 of an online heliostat field characterization system and in WP3 "Smart receiver control solutions detail engineering" with the development in task 3.2 of a high irradiance measurement system. Moreover, CIEMAT will participate with TEWER, DLR and CSPS on different tasks that will be performed at PSA. Most of the different solutions developed during the 3-year project will reach a 7-8 TRL and will be tested in the Cerro Dominador CSP plant (100MWe, 17.5h of storage and 25 years of expected lifetime).

Figure 22. View of Cerro Dominador commercial power tower plant in Chile

More Efficient Heliostat Fields for Solar Tower Plants – HELIOSUN.

Participants: CIEMAT, Universidad de las Islas Baleares.

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Loreto Valenzuela, lvalenzuela@psa.es

Funding agency: Ministerio de Ciencia e Innovación, Proyectos de Generación de Conocimiento 2021.

Background: Among the existing concentrating solar technologies, central receiver tower technology has the greatest potential for improvement. Amid all the components of the technology (solar field, receiver, energy storage system and power block), the cost reduction in the solar field, formed by thousands of heliostats, would have the greatest impact on the cost reduction of a central receiver plant.

Objectives: The present project approaches cost reduction on heliostat fields from 3 different but complementary points of view (control, extinction model, software). These three approaches will allow improving the operation of solar tower plants as a whole, optimizing in particular the operation of the solar receiver and the solar field, increasing the annual electricity generation and therefore the technical and economic efficiency of these systems.

Achievements in 2022: An artificial vision system with object recognition based on neural networks is proposed, which allows the closed-loop tracking control of the heliostats in the solar field. This system, consisting on the installation of a low-cost camera and processor in each one of the heliostats in the solar field, will eliminate the positioning sensors and therefore improve the heliostat tracking accuracy, improving the concentrated solar radiation distribution on the solar receiver surface. During this year, images have begun to be taken with two of these low-cost cameras installed in two separate heliostats.

Solar extinction in PSA is being measured daily with the aim of obtaining a typical year for this variable that allows reliable models to be incorporated into tower plant designs.

A ray-tracing simulation software, based on OTSun, is being developed, including a more accurate prediction of the behaviour of a solar tower plant with central receiver considering spectral analysis, as well as including all the experimental results presented above.

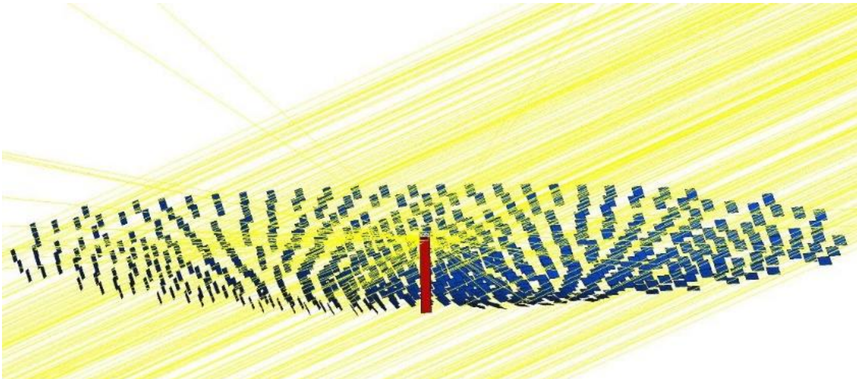


Figure 23. Solar tower power plant based on the PS10 power plant simulated with OTSun.

Heliostat ATH146 evaluation.

Participants: TEWER, Acciona, CIEMAT-PSA.

Contact: Rafael Monterreal, rafael.monterreal@psa.es
Raúl Enrique, raul.enrique@psa.es

Private funding: TEWER.

Background: This heliostat is an evolution of the HTW135 model, the prototype which was assembled and evaluated at PSA in 2017. According to the manufacturer, the new ATH146 heliostat prototype, a product of the Acciona-TEWER collaboration, increases its reflective surface to 146 m^2 and incorporates 32 facets of new innovative configuration, composed of a high-reflectance solar mirror, supported by only three linear profiles, with a total of six attachment points to the heliostat's metal structure. This innovative facet concept allows to produce facets with curvature in both axes in a very simple and easily adjustable way, being one of the axes curved during the facet production process and the other axis during the process of edging and fastening of the facets to the heliostat.

Objectives: Fabrication, assembly, test and evaluation campaign at the PSA Heliostat Prototype Test Platform (ICTS CESA-1) facilities in 2021-22.

Achievements in 2022: The PSA Testing and Evaluation Campaign was successfully completed this year.

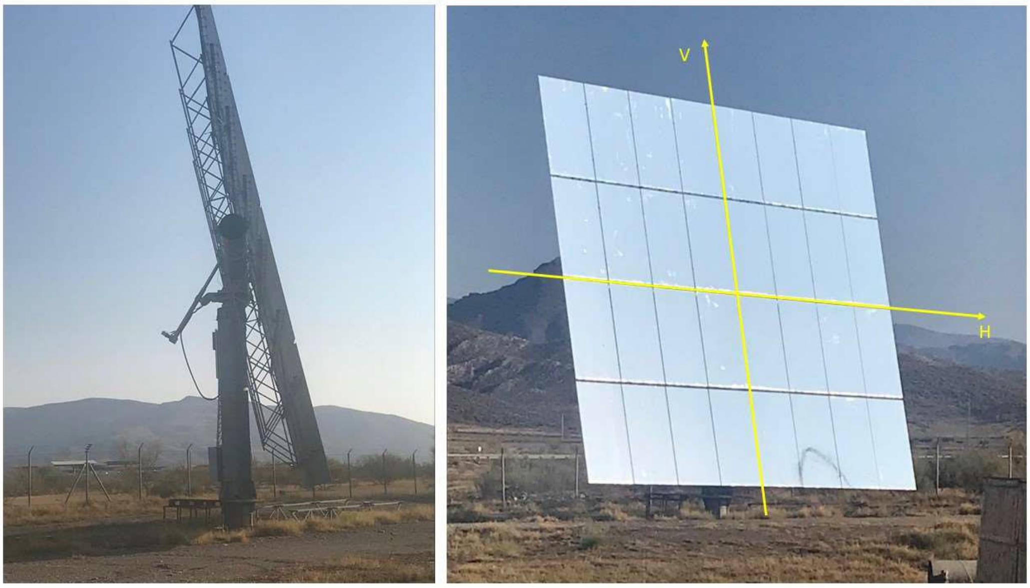


Figure 24. Acciona-TEWER Heliostat ATH146 at the PSA

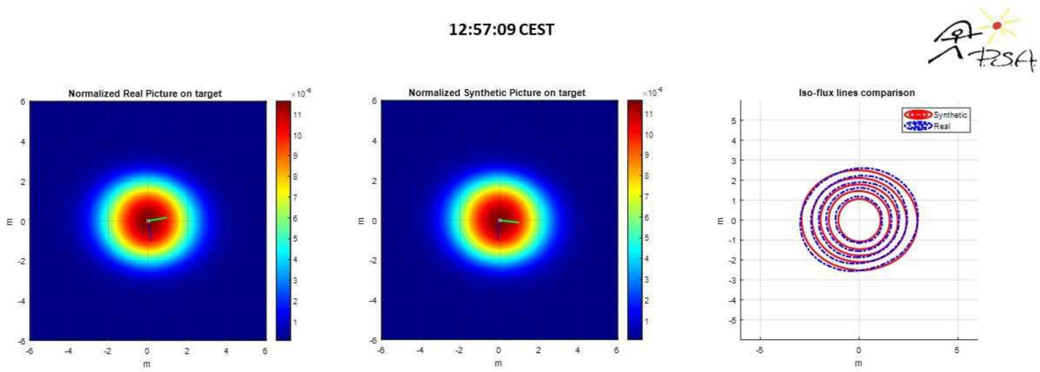


Figure 25. Optical quality test result at solar noon

Components' and Materials' Performance for Advanced Solar Supercritical CO2 Power Plants, COMPASsCO2

Participants: DLR (coordinator), CIEMAT (Plataforma Solar de Almería-PSA and Materials for Energy Interest Division-DMXE), CVR, Dechema, John Cockerill, Jülich, Ocas, Ome, Saing-Gobain, Sugimat, University of Birmingham, VTT.

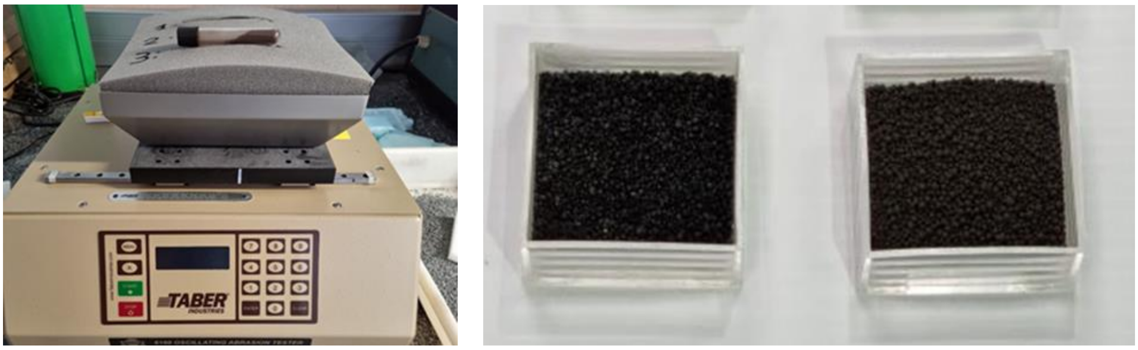
Contacts: Gema San Vicente, gema.sanvicente@ciemat.es

Funding agency: EU-H2020- NMBP-ST-IND-2018-2020.

Background: The development of systems that can reach higher temperatures than those currently applied on commercial solar power plants (390 °C of thermo-oil and 560 °C of molten salt) allow the connection of solar energy into highly efficient and/or innovative systems. These systems could be high-temperature thermodynamic cycles (as Brayton cycles) and chemical or high-temperature processes as those related to solar fuels, materials processing and/or production or synthesis of chemicals. Among the media currently investigated to allow temperatures of 1,000 °C or more in high-temperature solar receivers, the use of solid particles have the advantage that they can also be directly used as the thermal energy storage medium.

Objective: The project is focused in the integration of two innovative processes: a CSP solid particles system coupled to a highly efficient s-CO_2 Brayton power cycle for electricity production. For this purpose, the project aims to research on tailored particles and alloy combinations that will be produced ant tested to withstand the extreme operating conditions in terms of temperature, pressure, and abrasion to validate a particle/s-CO_2 heat exchanger.

Achievements in 2022: This project is at its halfway point in 2022 and significant progress has been made this year. PSA-CIEMAT's contribution at this point of the project is focused on the application of absorber coatings on the novel particles developed in the project to be used in the solar receiver and in the heat exchanger. High values of solar absorptance and high resistance to abrasion processes by particle-particle collisions are required. After studying the application of absorber coatings on the state of the art particles, the coating preparation conditions have been optimized to reach the better properties. It includes method of application, composition of the precursor solutions and sinterization conditions. Thus, solar absorptance values of 98 % have been achieved on the novel particles, increasing the values of the bare particles in 10 percentage points. Moreover, an abrasion test was designed to study the processes of degradation via particle-particle collisions by means of oscillating movements. The results showed that the solar absorptance of the coatings developed by CIEMAT decreases only in a 3.5 % after 1,600 accumulated abrasion cycles.



(a) (b)

Figure 26 (a) Collision particle-particle experimental test. (b) CIEMAT coated novel particles before (right) and after (left) 16,000 abrasion cycles.

Characterization of optical properties of particles for CSP.

Participants: DLR (coordinator), CIEMAT, DLR, ENEA, NREL, SANDIA, Universidad de Barcelona.

Contacts: Gema San Vicente, gema.sanvicente@ciemat.es
Ángel Morales, angel.morales@ciemat.es

Funding agency: SolarPACES (International Energy Agency)

Background: The application of particle receivers in high temperature CST technologies is achieving great interest because of the advantage of reaching higher operating temperatures and then higher receiver efficiencies. However, the optical characterization of them involves the challenge to measure through a transparent cover, since most UV/VIS/NIR and FTIR spectrophotometers require vertical placement of the sample in the measurement device and the particles need to be retained inside a container with a transparent cover facing the measurement port. There is currently no guideline or standard available establishing a common measurement procedure or correction function.

Objective: The main goal of this project is to define a proper protocol to characterize optically particles that can be used in particles receivers of high temperatures CST technologies. With this aim, a round robin test (RRT) for measuring particles of different properties with different methodologies and equipment was done. Furthermore, the experimental results will be assessed by the development of an optical model that considers the window-particle system and stablishes the correction formulas to be applied in the experimental data to get the intrinsic absorptance or emittance of the particle-layer.

Achievements in 2022: During this year, CIEMAT participated in the round robin test by characterizing different types of particles and using different measurement methods. The comparison of the results obtained from all the participants and the application of the correction formulas established by the developed optical model, have enabled the possibility to obtain a simple method to correct optical reflectance measurements of particle films through windows. With the results, a guideline document to determine solar absorptance and thermal emittance, has been prepared and open-access published on SOLARPACES Task III website. It includes the protocol of direct measurements with handheld reflectometers/emmisiometers as well as lab equipment through windows and associated correction methods.

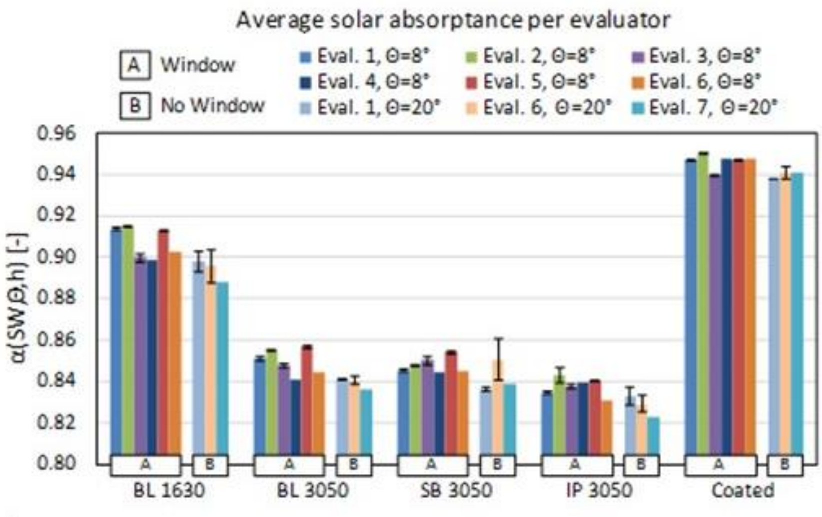


Figure 27. Comparison of solar absorptance values of different types of particles (BL 1630,BL3050, SB 3050, IP 3050 and coated) obtained by all participants in the round robin test.

Innovaciones tecnológicas para la mejora de la viabilidad de las plantas termosolares de concentración (INTECSOL)

Participants: CIEMAT-PSA

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Gema San Vicente. gema.sanvicente@ciemat.es

Funding agency: Ministry of Science and Innovation. Call “Proyectos de Generación de Conocimiento 2021. (PID2021-126664OB-I00).

Background: The current market situation stablishes two dominant concentrated solar thermal (CST) technologies, the well-known and mature parabolic-trough collectors (PTC), and solar tower (ST) systems. However, the new generation of the CST plants requires technological innovations for improving its feasibility either reducing cost and/or increasing efficiencies.

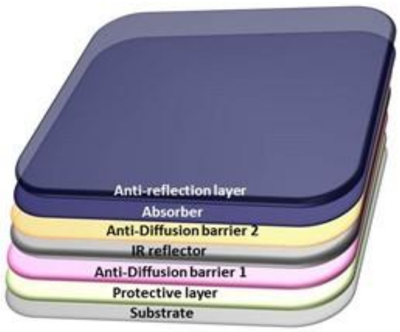
Objective: The INTECsol project focuses its R&D activities in the main solar components of a CST plant, the solar reflector and the receiver (for both PTC and ST systems), with the analysis and development of new components, and the implementation of improved materials and updated component features. These activities are aimed at improving efficiency and reducing costs.

Achievements in 2022: This project started in September 2022 and will last until August 2026. The work to be done in relation with the reflectors is mainly focused in two actions:

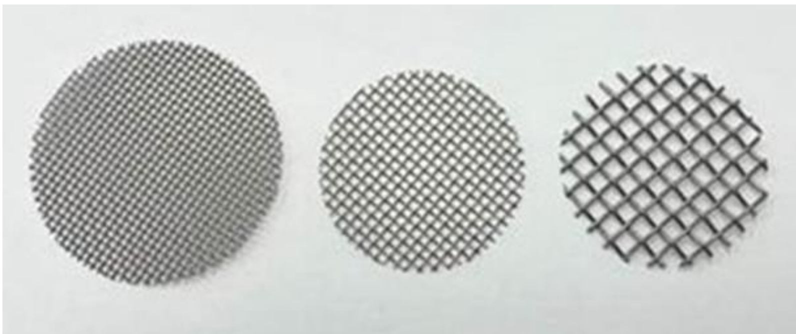
a) The improvement of the overall performance of solar reflectors through the application of anti-soiling coatings, the development of a corrosion prediction system to evaluate and anticipate the performance of the solar field, and the study of the degradation mechanisms due to ultraviolet radiation, dependent on temperature and humidity.
b) The study of a self-aligned heliostat for ST systems where the size of each facet with respect to the total area will be analysed in order to reduce mechanical stresses and thus increase its useful life.

In the case of receivers, three ambitious actions are planned:

a) The development of new selective and non-selective coatings for tubular receivers in ST systems.
b) The thermal and hydrodynamic optimisation of a commercial wire mesh volumetric receiver for ST systems, as well as the study of the influence of a selective coating and the analysis of its implementation in a plant scheme.
c) The study of soiling effect and new anti-soiling coatings on the complete section of the glass cover of PTC.



(a)



(b)

Figure 28. (a) Proposed structure of the selective absorber for high temperature tubular receivers. (b) Different mesh configurations to be studied in the optimisation of volumetric receivers.

Soiling measurement of solar reflectors

Participants: CIEMAT (coordinator), DLR, ENEA, Fraunhofer ISE, University of Zaragoza, NREL, TSK, Abengoa and Rioglass.

Contacts: Aránzazu Fernández García, arantxa.fernandez@psa.es

Funding agency: SolarPACES (International Energy Agency).

Background: Although the SolarPACES Reflectance Guideline gives recommendations for the use of reflectance measurement instruments and their calibration, it is only focused on clean and new reflectors. It has been demonstrated that even using well calibrated reflectometers, the achieved results differ substantially for different instruments and measurement parameters when measuring soiled reflectors in the solar field.

Objectives: The main goal is a new SolarPaces Guideline for soiled reflectors, to ensure the reliability of specular reflectance measurements on soiled mirrors. It is approached through outlining the proper features of the field reflectometers and obtaining correlations between the reflectance values given by different field reflectometers and the complete reflectance information determined with lab equipment.

Achievements in 2022: During 2022, the last activities were performed and the project was properly ended. In particular, the WP2, which is devoted to obtaining correlations between portable and advanced lab instruments, was completed. Both naturally soiled samples and the coupons produced in 2021 with the sand blast chamber, were measured both with portable and laboratory equipment by different institutions to estimate conversion functions that will allow deriving more representative reflectance values from the data acquired with field instruments.

All the results achieved in WP2 were included in a final deliverable tittle "Recommendations for reflectance measurements on soiled solar mirrors, V0.1, July 2022", specially devoted to describe the adaptation of solar field reflectometer readings to solar field optical properties, both using transfer functions and the calibration coupons. In addition, this document also includes a deep revision of the soiling measurement devices (handheld reflectometers, irradiance based soiling sensors, scattering sensors and image-based methods), and a description of the measurement point selection and the solar field averaging methods.

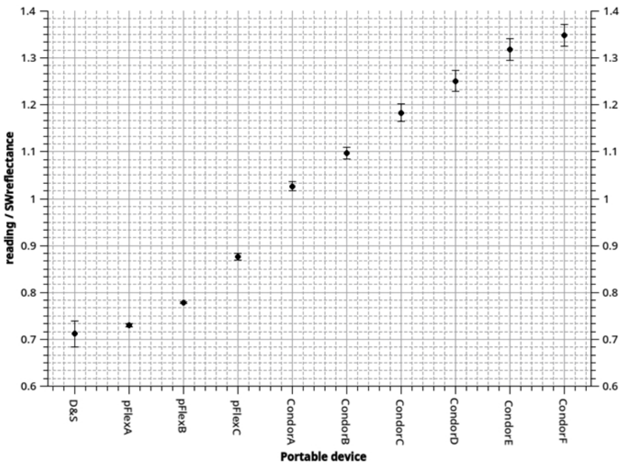


Figure 29. Expected ratio between in-field cleanliness readings and the solar near-specular reflectance of interest for an specific commercial plant located in the United States

GreenCoat

Participants: DLR, AGC, MIPA, CIEMAT

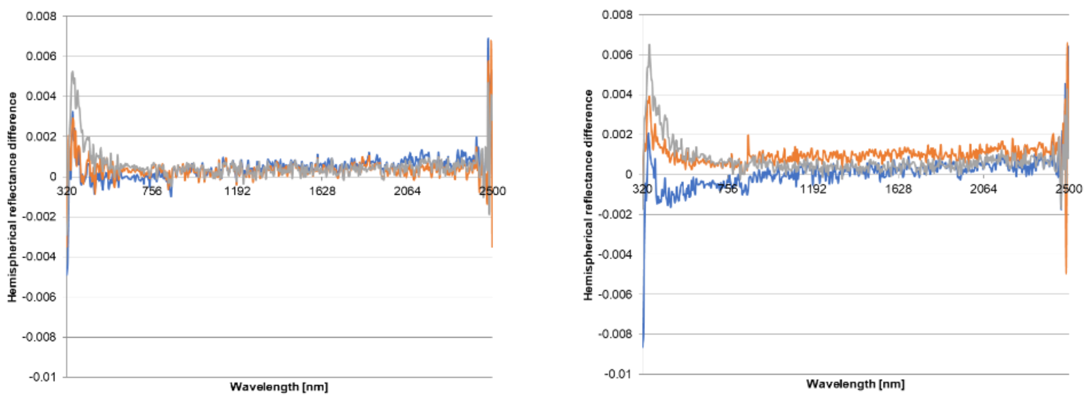
Contact: ricardo.sanchez@psa.es

Funding agency: Ministry for Economic Affairs and Climate Action (BMWK)

Background: State-of-the-art solar reflectors consist of a silvered 4-mm low-iron glass protected by a copper layer and 2 or 3 protective paint layers. The protective paint base layer usually contains up to 10 wt.% lead as corrosion inhibitor. However, lead pigments are toxic and carcinogenic. For these reasons, lead needs to be removed from solar mirrors.

Objectives: The main goal of the project is the development and testing of lead-free mirror coatings, finding alternative corrosion inhibitors to protect the metallic silver layer during its expected lifetime of more than 25 years in a harsh desert environment.

Achievements in 2022: During this first year of the project, a series of accelerated ageing tests have been carried out at the OPAC facilities in order to estimate the performance of a new lead-free mirror coating developed by MIPA, including the following tests: Neutral salt spray test (NSS), Copper Accelerated Acetic Acid Salt Spray test (CASS), Condensation test (COND), Thermal Cycling / Humidity test (TCH), Damp Heat test (DH), and UV / Humidity test (UVH). According to the first results of the accelerated aging tests, the lead-free mirror samples showed promising results. As example, Figure 30 shows the reflectance difference after 1920 hours in the Neutral Salt Spray test according to ISO 9227 for the leaded reference samples and the novel lead-free mirrors. For both materials, the degradation is almost negligible (below 0.2 % of solar-weighted reflectance loss), indicating excellent corrosion protection even in absence of lead pigments.



(a) (b)

Figure 30. Hemispherical reflectance difference (= initial reflectance - reflectance after 1920 hours of Neutral Salt Spray testing) of regular solar mirrors (a) and lead-free solar mirrors (b). Three replicates have been tested in the Neutral Salt Spray test.

New nanostructured coatings for efficient absorption of solar radiation in CSP systems, HIPIMSOLAR

Participants: ICMSevilla - CSIC (coordinator), CIEMAT and University of Seville.

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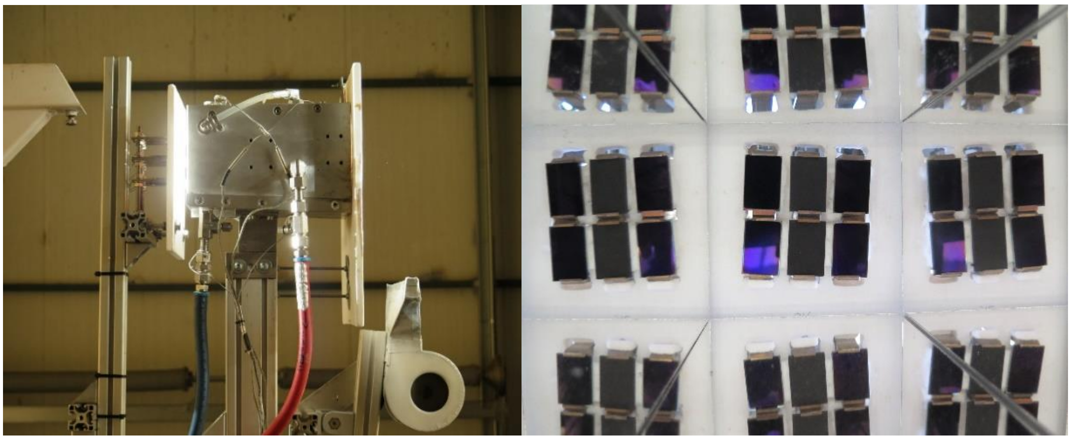
Funding agency: Andalusian Regional R&D Programme (2020-2022). FEDER Programme for R&D&I in Universities and Research Centres. P18-RT-2641.

Background: Recent studies focus on the development of new high-temperature selective solar coatings to improve the performance of concentrating solar power (CSP) plants. The aim is to maximise absorption in the visible and near-infrared regions, and minimise thermal emissivity in the far-infrared. Nowadays, solar towers do not use selective coatings but absorber coatings with high absorptance (α>0.95) as well as high emittance (ε>0.8). Their degradation at temperatures above 550 °C makes frequent renewal necessary.

This project is carried out through the collaboration of two research groups, one from the Materials Science Institute of Seville ICMS-CSIC (TEP-958) and the other from the Plataforma Solar de Almería CIEMAT-PSA (TEP-247).

Objective: This project is focused in the development, testing and characterization of new solar selective absorber coatings, suitable for working at high temperatures, in the order of materials currently in use in solar thermal concentrating technologies (500 °C in vacuum - medium concentration; 800 °C in air - high concentration). Different stacks are prepared in multilayers by the novel sputtering technology, evaporating the materials via high-energy impulses (HiPIMS - High Power Impulse Magnetron Sputtering).

Achievements in 2022: A new test bench for testing of new nanostructured coatings has been developed and tested at CIEMAT-PSA SF40 Solar Furnace. Two set of nanostructured coatings developed by ICMS-CSIC have been mounted in the new test bench to check their behaviour in real solar conditions. Solar ageing of new coatings has been carried out under real CSP conditions. Solar fluxes were controlled to limit the maximum working temperature at 650 °C and their optical performance was compared with commercial paint Pyromark©, deposited on similar substrates during 50 hours. The optical properties have been measured using portable equipment typically used in the industry as well as reference spectrophotometers in laboratories OPAC, OCTLAB and Materlab.



(a) (b)

Figure 31. (a). New test bench for solar ageing of metallic specimens working under solar real condition at solar furnace SF40. (b) New nanostructured coatings developed by ICMS-CSIC.

Smart Thermal Storage for Decarbonisation of Energy Sector, STES4D

Participants: Universidad de Zaragoza (coordinator), Universidad del País Vasco, CIEMAT

Contact: Rocío Bayón, rocio.bayon@ciemat.es

Funding agency: Ministerio de Ciencia e Innovación, Proyectos Estratégicos Orientados a la Transición Ecológica y a la Transición Digital (TED2021)

Background: As gathered in the PNIEC 2021-2030, there is an imperative need to promote solutions for the development of thermal renewable energies. However, due to their inherent intermittent nature, this can only be achieved if efficient and technologically mature thermal energy storage (TES) systems are available.

Objectives: In this context, STES4D project aims to contribute to: (i) the deployment of TES systems to reduce CO_2 emissions related to the thermal energy demand in buildings and industry and, (ii) to enable the increase of renewable sources integration into energy production and management. The scope is not limited to TES systems for a direct integration of renewable thermal sources, such as solar thermal or industrial waste heat, but also to increase the renewable share in power to heat or polygeneration systems (e.g. energy communities) improving the flexibility of energy grids. STES4D is a coordinated project and the Thermal Energy Storage Unit of CIEMAT is responsible for the subproject STES4D-mat, which is focused in the selection, characterization and validation of the storage materials (mainly PCM) to be implemented in the different storage applications considered in the project.

Achievements in 2022: The project started in December 2022, so no activities have been developed yet.

Storage Research Infrastructure Eco-System, StoRIES

Participants: KIT (coordinator), AIT, CIEMAT, CLERENS, CNR, CSIC, DTU, EASE, ECCSEL, ERIC, EDF, EERA, ENEA, ENI, FZJ y SINTEF

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Funding agency: EU, H2020-LC-GD-2020

Background: According to the European Green Deal goals, new energy storage technologies will supply more flexibility and balance in the grid by providing a backup to intermittent renewable energy and contributing to seasonal energy storage challenges. However, above all, the main challenge for energy storage development is economic.

Objectives: The main objective of StoRIES project is to create an industrial research ecosystem at European level in the field of energy storage by providing access to high-level research infrastructures and services and by developing specific services and tools with the aim of improving materials and optimizing the hybrid energy systems. The StoRIES project also includes socio-economic and environmental aspects of such systems, the identification and involvement of potential industrial users, the elaboration of technological roadmaps and different training and dissemination activities. CIEMAT participates in StoRIES project through various Research Units that belong to different Departments and offers three research infrastructures to be accessed by external users.

Achievements in 2022: Thermal Energy Storage Unit is participating in task 3.1 (Materials for devices), in which a database with the materials considered most important for energy storage is being created. The database has been initiated by FZJ and is being expanded to add new materials with the contribution of the different partners of the project. The unit contributes to this database with its knowledge about thermal storage media. During this year, the members of the unit have also attended the different meetings and workshops organized by the project, especially Rocío Bayón, who is the IP of this project on CIEMAT's side. It is important to mention that the 3rd Project Meeting of StoRIES took place at PSA so that all partners could visit not only one of the installations offered to access in the project (MOSA) but also the rest of research infrastructures located at PSA.

Small-Scale Solar Thermal Combined Cycle, POLYPHEM

Participants: CNRS (coordinator), CEA, CIEMAT, Arraela, Fraunhofer, Kaefer Isoliertechnik, Orcan, Euronovia, Aalborg CSP

Contact: Esther Rojas: esther.rojas@ciemat.es

Funding agency: EU, H2020-LEC-2016-2017

Background: With the objective of increasing the flexibility and improving the performance of small solar tower power plants, the concept of the project consists in implementing a combined cycle formed by a solarized micro gas-turbine and a Rankine organic cycle machine, with an integrated thermal storage device between the two cycles.

Objectives: The project will build a 60 kW prototype plant with a 2 MWh thermal storage unit and will validate this innovative power cycle in a relevant environment (TRL 5), assess its technical, economic and environmental performances and establish the guidelines for its commercial deployment.

Achievements in 2022: In this project, the main contribution of CIEMAT was de design of a thermocline storage tank with a structured filler made of concrete and oil as heat transfer fluid. During 2022, the design of the storage tank had to be adapted in order to optimize its construction time and cost. Both the instrumentation and testing matrix required for its evaluation were defined. The project benefitted from the great experience of the Thermal Energy Storage Unit in commissioning thermal storage prototypes. Unfortunately, an important leakage of the heat transfer fluid that could not be solved prevented the tank to be tested as it was planned. The project ended in August 2022 after having an extension of a few months due to the Covid19 Pandemic.

Thermochemical HYDROgen production in a SOLar structured reactor: facing the challenges and beyond (HYDROSOL-BEYOND)

Participants: APTL (Greece), DLR (Germany), Hygear (Netherlands), ENGICER SA (Switzerland), SCUOLA UNIVERSITARIA PROFESSIONALE DELLA SVIZZERA ITALIANA (Switzerland), COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (France), ABENGOA HIDROGENO SA (Spain) and CIEMAT-PSA (Spain).

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Alfonso Vidal, alfonso.vidal@ciemat.es

Funding agency: European Commission, H2020-JTI-FCH-2018-1

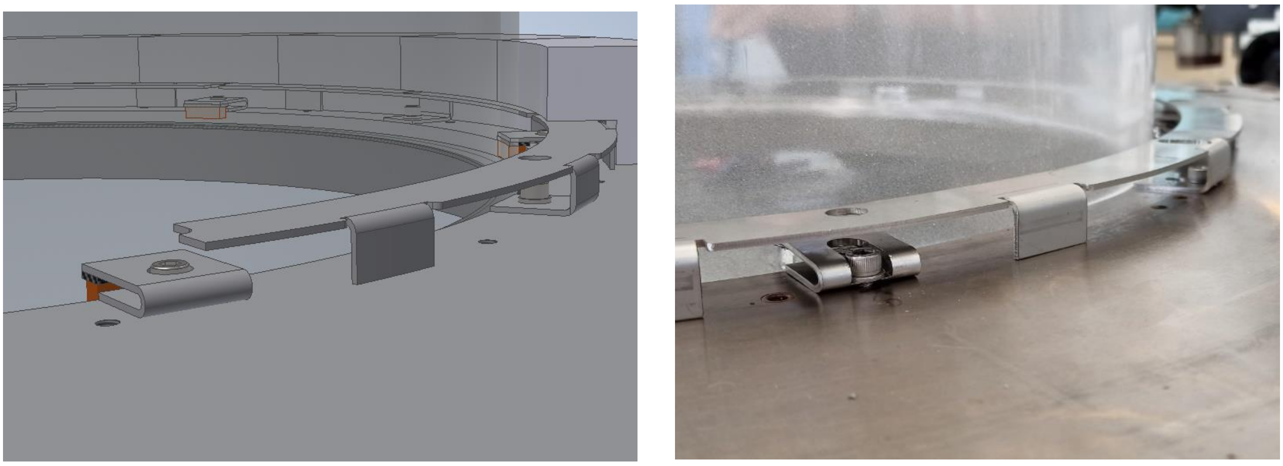
Background: The HYDROSOL-Beyond project is a follow-up of the HYDROSOL projects: HYDROSOL II (2006-2009), HYDROSOL-3D (2010-2013) and HYDROSOL-Plant (2014-2018) which required an upscaling of the current solar reactor technology from 100 kW to 750 kW and the development of all aspects in the solar receiver plant such as heliostat field, monitoring and control or feedstock conditioning and hydrogen storage.

HYDROSOL-beyond is an ambitious scientific endeavour aiming to address the major challenges and bottlenecks identified during the previous projects and further boost the performance of the technology via innovative solutions that will increase the potential of the technology's future commercialization.

Objectives: The main objectives of the project are summarized above are: (1) Improvement of the stability, cyclability and performance of the redox materials (1,000 cycles or 5000 hours of operation). (2) Design novel solutions for high temperature solid-solid and solid-gas heat recovery (higher than 50 %). (3) Embed and validate smart solutions to minimize the consumption of auxiliaries like flushing gas. (4) Design and development of intelligent systems and a smart process of control and automation, including predictive and self-learning tools.

Achievements in 2022: During 2022, two experimental campaigns were carried out to evaluate the feasibility of the innovated solutions of the quartz window fixation instead of silicone glue. Previous tests demonstrated that the silicone glue limits the maximum allowable temperature of the reactor and consequently affects the nominal conditions of the thermochemical process.

New design incorporates flexible clamps that hold down the quartz window to the flange of the main vessel. During the evaluation of these designs, a careful thermal test protocol was used to heat the reactor at temperatures 1,000 °C, 1,100 °C and finally over 1,200 °C, and demonstrated the effectiveness of the new design.



(a) (b)

Figure 32. Window fixing with clamp sheets. (a) CAD drawing. (b) real hardware.

This development has been chosen for its novelty and has been published on the EU Innovation Radar public website as an outstanding innovation developed in this EU project. Title of the innovation: [High temperature proof design for the attachment of large domed quartz windows to metal flanges].

Finally, a chemical experimental campaign was carried out in summer 2022 whose objective was to evaluate the H_2 production plant with the new window design that allowed to operate at temperatures of 1,200 °C.

A Lunar CHEMical In-Situ resource utilization Test plant. ALCHEMIST Phase A (ALPHA)

Participants: Space Applications Services (Belgium), CIEMAT-PSA (Spain), Airbus Defense and Space (Germany), SINTEF (Norway), Abengoa (Spain), Aavid Thermacore (UK), Technical University of Munich (Germany), Vrije Universiteit Amsterdam (Netherlands), Centre de Recherches Pétrographiques et Géochimiques (France), Centre Terre et Pierre (Belgium), CBK (Poland)

Contact: Thorsten Denk; tdenk@psa.es

Funding agency: European Space Agency, Contract ITT AO-9107

Background: The European Space Agency (ESA) planned to send a mission to the Moon to demonstrate In-Situ Resource Utilization (ISRU) on the lunar surface. ISRU means using local resources, especially minerals, to produce useful goods such as air (oxygen), water, metals, construction materials, or rocket propellant. In preparation for the mission, ESA issued several Invitations To Tender (ITTs) for detailed preparatory studies. This project was one of the selected participants. It is the follow-up to the Alchemist project (ESA contract ITT AO-9107), which was carried out in 2018.

In the years before, at the Plataforma Solar de Almería (PSA), a full-scale test plant capable of reducing ilmenite (a common mineral on the Moon) using hydrogen and concentrated solar power to produce water was designed, built and tested in the Oresol project. The knowledge and practical experience gained in Oresol was the decisive advantage for PSA to be invited to participate in the ITT.

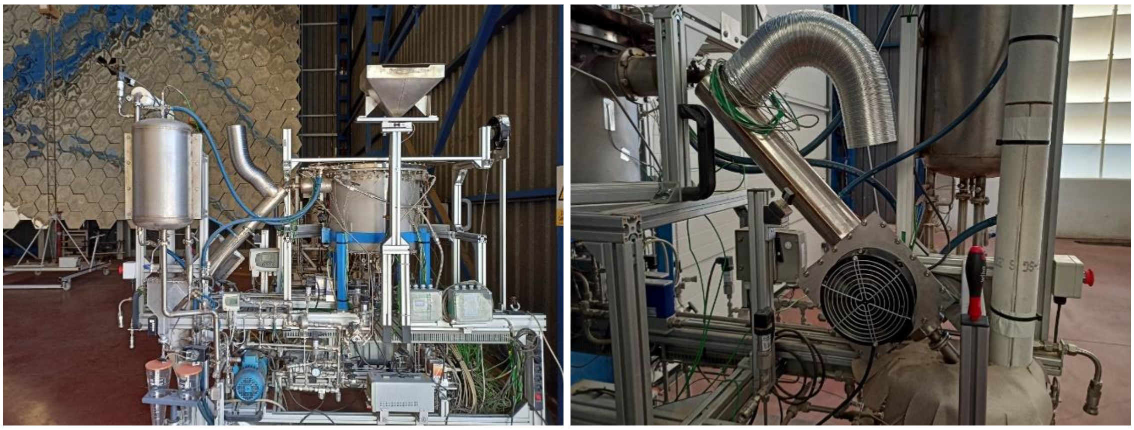
The ALCHEMIST project was the first ESA payload study to define the high-level details of a lunar ISRU payload. The concept selected for operation was the hydrogen reduction process.

Objectives: The main goal was to define the hardware of a lunar hydrogen reduction plant. This included subsystems for lunar sand (regolith) mining, pre-processing such as sieving or enrichment, regolith processing with hydrogen at 900 °C, and fluid management for hydrogen supply, recirculation, and extraction and storage of product water. The mission objective is to produce 100 g of water from lunar regolith.

Achievements in 2022: The Alchemist project was originally scheduled to end in April 2020. Due to some delays, the final project presentation meeting was postponed to January 2021. Nevertheless, work continues at PSA with the fully developed and operational Oresol reactor. The main objective of the tests is to advance the development of the technology and to obtain much more detailed operational and scientific data for further Alchemist editions. Due to the low priority of this activity, the solar tests scheduled for the end of 2022 have been postponed to 2023. However, some progress has been made in improving the hardware.

On the one hand, the control computer was finally replaced by a newer one with an updated version of LabVIEW, the software used for data acquisition and processing. On the other hand, the formerly water-cooled cooler C1 was replaced by an air-cooled cooler. This reduces the cooling power and, in particular, allows much better control of the temperature of the reactor's off-gas entering the particle separator. As a result, the heat-up time of this unit has been halved to less than one hour and, in general, its operating temperature can now be kept well above 100 °C to prevent unwanted condensation of the product water. Figure 33 shows the new cooler.

The plans for 2023 include, besides some minor modifications (simplifications) of the upstream piping, the installation of the new filter with a 20x increased filtering area, and the continuation of the system's operation.



(a) (b)

Figure 33. Oresol modified (air) cooler C1. (a) System view. (b) Close up view.

Boost to the solar thermal H_2 production via the development and validation of new materials for ceramic solar receivers with improved durability (HIDROFERR)

Participants: CIEMAT-PSA and ITC-AICE (Institute of Ceramic Technology) in Castellón.

Contacts: Diego Martínez, dmartinez@psa.es;
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Funding agency: Spanish State Research Agency

Background: The partners will re-take former collaborations and push forward a joint activity in developing the optimal materials and operating procedures for improved feasibility of hydrogen production via solar thermochemistry.

A first step in that direction is to achieve the goals of this project: develop combinations of ceramic and metallic materials able to deliver high hydrogen yields under concentrated solar radiation. The secondary goals would be to develop permanent testing infrastructures and a multidisciplinary R&D team to keep going this joint endeavour.

Objectives: 1. Find out combinations of receiver materials (ceramic substrate plus metal oxide coating) that significantly improve currently reported reaction efficiencies and minimize operational issues. 2. Develop manufacturing paths for such combination of materials. 3. Determine the optimal operating conditions for a maximum yield of hydrogen, i.e. temperatures for reduction/oxidation steps, feed-in gases flowrates and pressures and cycle timing.

Achievements in 2022: During 2022, some candidate ceramic substrates have been tested at PSA's SF-40 facility. These ceramic samples have been exposed to open atmosphere, as the goal at this stage is just to determine the resistance to thermal cycling and not the kinetics of any thermochemical reactions.

These materials were provided by ITC, covering available ceramics or even 'ad-hoc' formulations seeking improved features concerning resistance to thermal shock at temperatures over 1400 °C. A higher number of samples will be manufactured and a physical and thermal characterization will be carried out before proceeding to WP2.

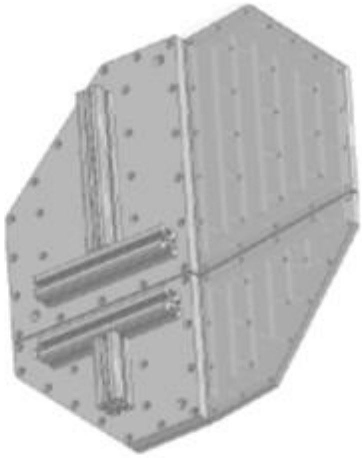

Figure 34. A homogenizer device fabricates during this phase

On the other hand, a flux homogenizer device has been designed and built in order to provide the sample with a solar flux map as flat as possible avoiding the 'Gaussian' effect of the concentrated radiation. Further tests, include to map the solar flux at the focal area and develop a thermal cycling procedure on dummy samples.

Finally, a campaign of thermal cycling between 1000 – 1400 °C will be carried out next year using this device with selected candidate ceramic substrate materials. The best candidates withstanding the above treatment will be selected for further deposition of metal oxides as catalysers.

Energía solar térmica de concentración en el sector del transporte y en la producción de calor y de electricidad, ACES2030.

Participants: IMDEA Energia (Coordinator), CSIC-ECI (Instituto de Catálisis y Petroleoquímica), UC3 – MISE(Universidad Carlos III de Madrid / Escuela Politécnica Superior), UNED-STEM (Universidad Nacional de Educación a Distancia / Escuela Técnica Superior de Ingenieros Industriales), UPMGIT (Universidad Politécnica de Madrid / E.T.S.I. Industriales), URJC – SOLAR (Universidad Rey Juan Carlos / Escuela Superior de Ciencias Experimentales y Tecnología) , CIEMAT-PSA and ABENGOA Hidrógeno (company subsidiary of the ABENGOA group) acting as industrial companies with active collaboration and interest in the possible exploitation of the project results.

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Esther Rojas: esther.rojas@ciemat.es

Funding agency: Programas de I+D en Tecnología 2018 de la CAM

Background: The new challenges regarding emissions abatement in preparation for the National Integrated Plan on Energy and Climate imply a twofold increment of renewable energy penetration with the aim to reach 32 % contribution in the energy mix (end use energy) in the horizon of the year 2030. The R&D program ACES2030 on concentrating solar thermal power assumes the new priorities for CSP and relies on important outcomes obtained during the previous programmes SOLGEMAC, S2009/ENE1617 and ALCCONES, S2013MAE2985.

Objectives: ACES2030 focuses its R&D objectives on three main challenges covering aggressive penetration of CSP within and use energy mix by 2030: Objective 1 – Renewable electricity. Objective 2 - Solar process heat. This objective is aligned with the integrated EC project INSHIP (Integrating National Research Agendas on Solar Heat for Industrial Processes) with the ultimate goal to prepare an ECRIA (European Common Research and Innovation Agenda) on this subject. Objective 3 – Solar fuels for transport.

Achievements in 2022: The contribution of the CIEMAT Hydrogen Unit to the present project is focused on technologies and processes for the production of H_2 and other alternative solar fuels for transport. In particular, the development of new materials for thermochemical cycles that aimed at clean hydrogen production.

These new materials should make it possible to reduce the high temperatures of the reduction stage of the material (1,400 -1,600 °C) as well as to improve the kinetics of O_2 and H_2 production.

The material used evaluated on the last phase of the project has been the perovskite $La_{0,6}Sr_{0,4}Fe_{0,8}Co_{0,2}O_3$, since it has been the material that has given the best results in the tests carried out during the last two years. The results obtained with this material are shown in Figure 35. In this last period, a durability test of the material $La_{0,6}Sr_{0,4}Fe_{0,8}Co_{0,2}O_3$, was carried out for 107 cycles according to the milestones committed in the project.

Each test lasts a full day since the activation and hydrolysis stages have a duration period of 7 hours to allow the system to stabilize and achieve stable O_2 and H_2 values. These tests have been carried out in the 1.5 kW loop coupled to a gas chromatograph and the operating conditions have been, activation temperatures of 1,300 °C and oxidation temperatures of 1,000 °C with a steam concentration of 30 %.

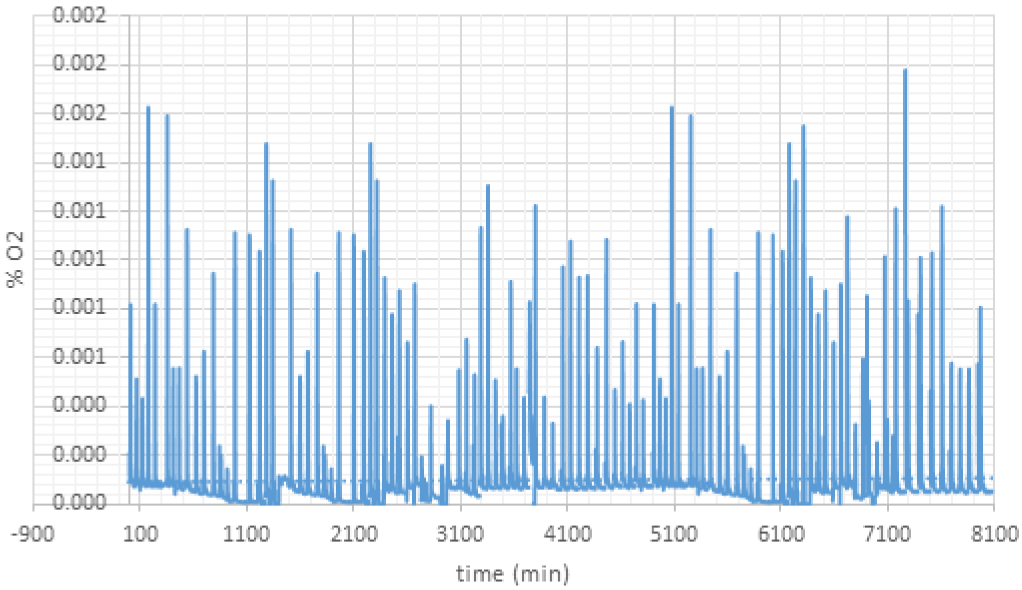

Figure 35. O_2 evolution cycling the material during the durability test.

A stability study of the material has been carried out by performing more than 100 cycles and using X-ray diffraction to demonstrate that the crystalline structure does not show any change. This result is of great importance in the synthesis of new perovskites since the material subjected to continuous cycling and structural stability is essential for the material to be viable.

Under the topic of thermal energy storage, CIEMAT contributes with studies on the methodology for validating phase change materials (PCM) for latent storage and on packed bed thermal storages at high temperature with atmospheric air as heat transfer fluid. The tests performed in year 2021 in the test facility ALTAYR were used to define a methodology able to evaluate the thermal contribution of the device where solid materials as fillers are tested. This methodology allows increasing the accuracy of the already presented procedure for calculating experimentally the volumetric thermal capacity of a filler by comparison with a well-characterized filler.

In relation to the validation of PCM as storage media, the work has been focused in the kinetic analysis of TGA data when evaporation is one of the degradation processes. The mathematical model used was the one proposed by some authors in 2003, which is based on Knudsen-Langmuir equation but considers the diffusion in the specific test conditions of the TGA (i.e. the geometry of the sample holder, the purge gas, etc.). This model was applied for the TGA measurements of different PCMs such as lauric, myristic, stearic and adipic acids and it has been seen that it reproduces the experimental curves quite well for different heating rates (Figure 36).

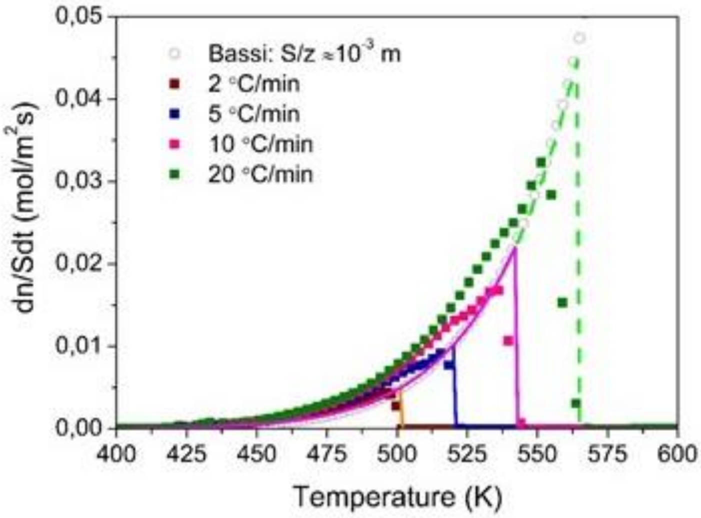

Figure 36. Comparison of the evaporation rate calculated from TGA measurements at different heating rates with that predicted with the calculations for the case of adipic acid.

The evaporation curves obtained with this model were subsequently adjusted to a conventional zero-order kinetic equation that, according to the literature, represents the evaporation processes. From this fitting, the value obtained for the activation energy is in the range of the values calculated by the Friedman isoconversional method which coincide with the evaporation enthalpy reported in the literature for each acid. The results from the kinetic analysis of TGA measurements will be compared with the results from the isothermal tests carried out in the oven in order to correlate the information obtained from both approaches and determine the limitations of TGA technique for establishing the degradation kinetics of PCM.

Solving Water Issues for CSP Plants, SOLWARIS

Participants: TSK (coordinator), CEA, DLR, CIEMAT, Crandfield University, Fundación Tecniker, Rioglass Solar, Ingeniería para el Desarrollo Tecnológico, FENIKS, Barcelona Supercomputing Center, BrightSource Industries (Israel) Ltd. AMIRES

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Funding agency: European Commission, EU-H2020-LCE-11-2017

Background: Water consumption is a major issue for the commercial development of CSP/STE plants in desert areas. Several technical innovations for water saving have been identified and some of them are already under development in the H2020 WASCOP project. SOLWARIS is somehow the continuation initiated in WASCOP.

Objectives: The main objective of SOLWARIS is the testing and validation in a real commercial environment for water saving in CSP/STE plants. These innovations include: anti-soiling coating for mirrors receiver tubes, advance cleaning systems, water recovery systems for the BOP and cooling tower effluents, cooling thermal energy storage and a plant O&M optimizer including soiling rate forecast.

Achievements in 2022: CIEMAT continued working in WP5, focused on the publication in Desalination Journal of the dynamic model of a Multi-effect evaporation plant or Water Recovery in a CSP plant and its validation at design point. Likewise, the modelling tool was used to optimize the operation of the plant with the purpose of the maximum recovered water production (which is equivalent to optimize the concentration factor) as function of the chemistry of the treated raw water.

Bio-mimetic and phyto-technologies designad for low-cost purification and recycling of water, INDIA--H2O

Participants: UOB (coordinator), PDPU, CIEMAT, AQP, AQPA, IHE, LEITAT, GBP, MOD, BGU, DAV, ACWADAM, JU, OPC, CETIM, AU, CEERI

Contact: Guillermo Zaragoza, guillermo.zaragoza@psa.es

Funding agency: European Commission, H2020-SC5-2018-2019-2020

Background: INDIA-H2O will develop, design, and demonstrate high-recovery, low-cost water treatment systems for saline groundwater and industrial wastewaters, focused on the arid state of Gujarat, with scarce surface water resources. Solutions will be demonstrated in small-scale rurally relevant low-cost systems, and a centre of excellence will be established in water treatment membrane technologies, design operation and monitoring.

Objectives: Develop novel batch-reverse osmosis technology for a 10-fold reduction in specific energy consumption with high water recovery (80 %) reducing operating costs. Develop forward osmosis at pilot scale for use in wastewater recovery applications including hybrid arrangements with reverse osmosis for further reduction in energy consumption. Develop business models, policy briefs and governance arrangements for adoption of the developed systems.

Achievements in 2022: CIEMAT's team coordinated the activities of WP4, focused on the development of ICT tools to enable remote monitoring, control and optimisation of the demonstration plants. CIEMAT also participated in the General Assembly and Consortium Meeting held in Gandhinagar in March, which included the opening of the demonstration facilities and the first operation of the solar-powered batch reverse osmosis plant at Pandit Deendayal Energy University. The second review meeting with the European Commission was held in May with successful feedback for the continuation of the project, and a further Consortium Meeting in Barcelona was attended in October.

Promoting energy-water nexus resource efficiency through renewable energy and energy efficiency, EERES4WATER

Participants: CTA (coordinator) (ES), US (ES), CIEMAT (ES), ITC (ES), UCC (IE), BRINERGY (ES), ENERAREA (PT), UEVORA (PT), RML (IE), CU (UK), ESPRIT (FR)

Contact: Diego Alarcón, diego.alarcon@psa.es

Funding agency: European Commission, INTERREG Atlantic Area Programme

Background: According to the priorities establish1ed in the Research and Innovation Strategies for Smart Specialization (RIS3), sustainable solutions to technological advancement of the energy and water sectors with regard for regional specific features are required, from industrialized to rural. Technological solutions should be adapted to different scenarios commonly exist in the Atlantic Area, specially to coastal areas and islands.

Objectives: EERES4WATER will enhance the institutional, technical and social framework to promote the direct use of renewable energy sources and energy efficiency in the water cycle by influencing related policies and introducing new processes and technologies. Main goal is to provide Atlantic Area stakeholders with the tools and instruments needed to overcome the Energy-Water nexus challenges and increase its utilization.

Achievements in 2022: During the last year of the project, a new experimental forward osmosis installation based on the use of biomimetic hollow fiber membranes (active layer of polyamide thin film composite with integrated Aquaporin proteins) has been commissioned. An FO process model has also been developed and validated for its combination with a MED plant as a regeneration system for the draw solution. This combination has led to improved thermal efficiency, a smaller water footprint (reduction of electricity consumption) and a reduction in the heat exchange area (lower investment cost) compared to a conventional MED plant. On another hand, we have collaborated with the Instituto Tecnológico de Canarias and the University of Seville by providing models of vacuum-assisted membrane distillation modules and have carried out studies of the levelized cost of water for scenarios of industrial production of desalinated water in the Atlantic area using this technology.

Next generation water-smart management systems: large scale demonstrations far a circular economy and society, WATER-MINING

Participants: TU DELFT (coordinator), SEALEAU, KWR, EURECAT, NTUA, SELIS, CIEMAT, DECHEMA, BRUNEL, UNIABDN, WaterEurope, HEXION, UNIPA, WETSUS, UAB, JIN, ACSA, ICCS, RHDHV, KVT, LARNACA, NEMO, ACCIONA, USC, JIIS, ADA, REVOLVE, ENoLL, WEI, LENNTECH, TITANSALT, ECSITE, SOFINTER, VSI, THERMOSSOL, NOURYON, FLOATING FARMS, MADISI

Contact: Guillermo Zaragoza, guillermo.zaragoza@psa.es

Funding agency: European Commission, H2020-SC5-2019-2.

Background: The project aims to face the challenge of ensuring access to clean water and sanitation by developing innovative solutions for the sustainable use of alternative water sources, including urban and industrial wastewater and seawater desalination. Water is considered as a resource, a consumable and a durable good. To capture the full potential of the circular water economy, different strategies are proposed for each of these three water forms, involving six sector-specific case studies.

Objectives: CIEMAT is responsible of one of the two sea mining case studies, aiming to demonstrate that solar thermal desalination can improve the sustainability of current desalination technologies by reaching higher concentration towards zero liquid discharge, producing high quality salts and water suitable for agriculture. A living lab will also be created.

Achievements in 2022: Tests were performed with nanofiltration of seawater for case study 2 at PSA, to evaluate different operating conditions and membrane performance. The solar-powered MED plant was setup for testing pre-treated with nanofiltration seawater at high temperatures. A meeting of the Community of Practice was held in February to discuss the roadmap of case study 2 and to analyse the market barriers identified in prior one-to-one meetings with stakeholders. A Consortium Meeting, as well as a General Assembly of the project, were held in September in Palermo to discuss the feedback of the first technical report of the project and to share all the experience in the societal aspects of the project. Also, the Living Lab on Sustainable Desalination was inaugurated at PSA in November, holding a co-creation workshop with the Community of Users.

Intelligent water treatment technologies for water preservation combined with simultaneous energy production and material recovery in energy intensive industries, INTELWATT

Participants: NCSR (Coordinator), CNR, CNRS, PPC, WG, TH KOLN, UoB, POLITO, CUT, BIA Group, Fuelics, IHE DELFT, Studio Fieschi, TECHEDGE, ACSA, UJ, REDSTACK, CIEMAT, Nijhuis Water, NOKIA GREECE.

Contact: Guillermo Zaragoza, guillermo.zaragoza@psa.es

Funding agency: European Commission, H2020-CE-SPIRE-01-07-09.

Background: The project will develop innovative, cost-efficient, smart separation technologies applied in energy- and water-intensive industries. Three case studies in electricity production, mining and electroplating facilities will demonstrate water preservation along with energy production and material recovery. The proposed solutions will also target zero liquid discharge while implementing maximum water reuse.

Objectives: CIEMAT participates in case study 2 in Castellgali (Barcelona), where a pilot plant will be built which will consist of an integrated reverse electrodialysis (RED) system and membrane distillation powered by solar energy to valorise a collector of brine from mining activities, with the aim of producing electrical energy and deionized water.

Achievements in 2022: Tests of different membranes at different operating conditions of Membrane Distillation were carried out at PSA's Desalination Laboratory. The layout of Case Study 2 demonstration was designed, coupling ultrafiltration of brine from mining activities, reverse electrodialysis for harvesting salinity gradient power from the brine and well water, and membrane distillation powered by solar energy for further water recovery from the mixed solutions. A model of the solar-powered MD pilot plant was installed at PSA for evaluation prior to the final deployment in Castellgali. The first progress report of the project was elaborated, presented to the Commission in a meeting in Athens, and subsequently approved. Two meetings of the Strategic Management Board were held online (February and July) to monitor the progress of the project and a Consortium Meeting was held in November in Sorrento (Italy).

Soluciones de refrigeración híbrida para ahorro de agua en aplicaciones solares térmicas (SOLHYCOOL)

Participants: CIEMAT

Contact: Patricia Palenzuela, patricia.palenzuela@psa.es
Lidia Roca, lidia.roca@psa.es

Funding agency: Agencia Estatal de Investigación-Proyectos de Generación del Conocimiento 2021 (Ref: PID2021-126452OA-I00)

Background: The need to reduce the water consumption in Solar Thermal Applications is increasing, especially because these applications have a larger market niche in areas with significant water shortages. This fact, together with the high water price, puts into question the cost-effectiveness of such applications and the sustainability of their implementation.

Objectives: The goal of this project is to advance in the hybrid cooling technology for its use in solar thermal applications at commercial scale, like Concentrating Solar Power plants and multi-effect distillation plants driven by solar energy and located inland, to subsequently achieve a reduction in water consumption in such applications. By using automatic control methods, an optimum management of the operation of the hybrid cooling systems in terms of water consumption should be achieved avoiding the penalty in the efficiency of the solar thermal applications in which the cooling systems are integrated thus, making the technology feasible from a technical and economical point of view.

Achievements in 2022: The design of two experimental campaigns to identify the main components of the pilot hybrid cooler (the Wet Cooling Tower (WCT) and the Air Cooled Heat Exchanger (ACHE) located at PSA have been completed and most of the experiments have been carried out. For the ACHE, a Box Box-Behnken design has been used, in which the cooling water flow rate and the inlet and outlet temperatures as well as the ambient temperature have been varied. In the case of the WCT, a factorial design (2^K) has been selected in which, apart from the same variables as in the previous case, the humidity has also been accounted. In addition, the modelling of the WCT has been developed in two ways: based on experimental data (artificial neural network) and based on physical equations. The latter has been done in collaboration with the University of Elche, and the comparison between both models will be presented in a congress next year. Finally, the design and experimental testing of low-level control loops have been already completed.

SOL-préndete: Didáctica y divulgación de la energía solar térmica de concentración con nuevas tecnologías de realidad aumentada y virtual

Participants: CIEMAT

Contact: Lidia Roca, lidia.roca@psa.es

Funding agency: Ministerio de Ciencia e Innovación, FECYT

Background: PSA is the largest research centre in Europe dedicated to concentrating solar power, desalination and photochemical technologies and is recognized as a Major European Scientific Facility and as a Singular Scientific and Technical Infrastructure (ICTS). One of the aspects that the Spanish Strategy for Science, Technology and Innovation 2021-2027 (EECTI) considers as fundamental is the strengthening of the ICTS, being some of the objectives to monitor the volume, efficiency and quality of the returns to society of the ICTS, to improve the use of results and to communicate and disseminate to society the benefits derived from the ICTS.

Although PSA actively participates in several outreach activities and there is a company external to CIEMAT (the *Centro de Visitantes*, CAV) in charge of managing the visits the facility receives (mainly from educational centres), it has been detected that a more active participation involving researchers is needed in order to make society aware of both the unique facilities and the research activities carried out at PSA.

Objectives: 1) Enrich education and outreach with digital tools, such as virtual and augmented reality; 2) bringing science closer to educational centres located in vulnerable neighbourhoods; 3) bringing research closer to pre-university students.

Achievements in 2022: During this year, the activities carried out by CIEMAT have been focused on: 1) making the project known to society (mainly through dissemination activities, such as "The night of European Scientists 2022"; 2) launching the project's social networks (@SOLprendete_psa, solprendete_psa) and updating them with content about PSA research and facilities; 3) designing workshops, visits and outreach talks related to the project; 4) organizing activities with educational centres; 5) collaborating with the Institute of Communications and Computer Systems (ICCS) of Athens, in the design of an augmented reality application to explain in a fun and didactic way the circular use of water with solar thermal energy.

European Twinning for research in Solar energy to (2) water (H2O) production and treatment technologies, SOL2H2O

Participants: UEVORA (Coordinator), CIEMAT, ITC, UNIPA.

Contact: Guillermo Zaragoza, guillermo.zaragoza@psa.es

Funding agency: European Commission, HORIZON-WIDERA-2021-ACCESS-03.

Background: Gathering the experience of three first class partners (Universidad de Palermo, Instituto Tecnológico de Canarias and CIEMAT) with some of the most outstanding background and research infrastructure, at European level, in the development of Solar-driven water production and wastewater treatment technologies, Sol2H2O aims at supporting University of Évora in the development and establishment of high-level research in this field. Sol2H2O seeks to develop and implement a common scientific strategy, with a strong focus on an enhanced capacity building of researchers, going beyond purely scientific capacities and strengthening their research management and administration skills. With the goal of developing Solar-driven Water-Energy Nexus solutions, Sol2H2O aims at creating a reference European facility for the development and testing of Circular Solar-driven Water Production & Treatment technologies, enabling the development of renewable gas or agricultural economic activities upon exploitation of sustainable water resources.

Objectives: Engaging three top-class leading partners around a scientific strategy for stepping up and stimulating scientific excellence and innovation capacity on Solar-driven Water-Energy Nexus solutions, Sol2H2O aims at enhancing network with the Coordinator Widening partner, raising its research profile through the exploitation of their staff and infrastructural synergies in the establishment of a reference European facility for the development and testing of Circular Solar-driven Water Production & Treatment technologies. Specifically, a solar desalination system with zero liquid waste will be developed, and CIEMAT will contribute with membrane distillation technology.

Achievements in 2022: The kick-off meeting took place in mid-December; the Consortium Agreement was discussed for signature in 2023.

Sustainable membrane distillation for industrial water reuse and decentralised desalination approaching zero waste, MELODIZER

Participants: POLITO (Coordinator), CNR-ITM, Amapex, SolarSpring Gmbh, Inotex Spol. s.r.o., Deltamem AG, Athinaiiki Zythopiia Anonymos Etairia, Wings ITC, Aquabiotech, IRES, BlueTech Research Ltd, CIEMAT, Aalborg University, Warrang Hub S.p.A., Polymem, EnGits GmbH, Fraunhofer ISE, Municipality of Eilat (IL).

Contact: Guillermo Zaragoza, guillermo.zaragoza@psa.es

Funding agency: European Commission, HORIZON-CL4-2022-RESILIENCE-01.

Background: MEloDIZER's overarching goal is to provide the needed step to transform membrane distillation (MD) and especially its core components, namely, membranes and membrane modules, into products for the benefit of industry and society. MEloDIZER implements high-performance membranes and modules in strategic applications of membrane distillation (MD), hence providing the decisive step for the success of MD.

Objectives: (i) creation of next-generation membranes and modules obtained with green and readily scalable approaches; (ii) rationally integrate the core innovative membrane and module components with energy and control systems that maximise their performance and enable the smart utilisation of renewable energy; (iii) demonstrate the performance of the next-gen membrane components in the overall system for the reduction of industrial waste streams, the reuse of water, the extraction of resources, and for the production of drinking water by decentralised and diffuse human-scale MD units; (iv) demonstrate the economic and environmental benefits associated with the implementation of the innovative membrane components and the resulting improved MD technology, also providing sustainable end-of-life management of membranes components and systems.

Achievements in 2022: The project started officially in December, the Consortium Agreement was discussed at the end of the year for signature in 2023.

Interdisciplinar cross-sectoral approach to effectively address the removal of contaminants of emerging concern from water, AQUALITY

Participants: Universita Degli Studi di Torino, Universita Degli Studi del Piemonte Orientale Amedeo Avogadro, CNRS, Ecole Polytechnique, Karadeniz Teknik Universitesi, LIQTECH International A/S, Societá Metropolitana Axque Torino S.p.A., CIEMAT, Panepistimio Ioanninon, Universidad Politecnica de Valencia.

Contact: Isabel Oller, isabel.oller@psa.es

Funding agency: European Commission, H2020- Marie Skłodowska-Curie Action (ITN) (GA 765860)

Background: The complex challenges of the production of safe and clean water requires different levels of action, which include the synthesis of green materials, the development of enhanced water treatment technologies, the implementation of effective legal tools against water pollution and the correct management of the present water treatment facilities.

Objectives: AQUAlity is a multidisciplinary, interdisciplinary and cross-sectoral European Training Network aiming to generate and promote 15 highly skilled scientists with the potential to face the present and future challenges concerning the protection of water resources from Contaminants of Emerging Concern and to develop innovative purification technologies more effective than conventional adsorption and biological treatments.

Achievements in 2022: The final meeting of the project took place in Ioannina (Greece) on 27th and 28th June organized by the Department of Chemistry (University of Ioannina). At this meeting, a summary of the main results achieved in each WP was presented by each responsible from the corresponding institution. Special emphasis was done in showing the main results gathered in each one of the ESR´s PhDs defended before the end of this MCSA project. In this sense, the work carried out by the Solar Treatment of Water unit has been part of WP3 (Enhanced photochemical methods for the removal of CECs and pathogens in water and wastewater), in which the ESR Ilaria Berruti has performed her PhD and in WP4 (Innovative hybrid NF/AOPs for CECs abatement), in which the ESR Dennis Deemter performed his PhD. Pictures of the final meeting can be found in Figure 37. In this project, WP5, which dealt with recruitment and training, was led by Isabel Oller, head of the Solar Treatment of Water Unit. She presented a summary of the activities carried out within the frame of this WP, including a list of points to be improved in future potential MCSA projects, related to the recruitment of ESRs as well as the organization of training and dissemination activities jointly with other MCSA projects. The project officially finished on September 30th 2022 after an approved non-cost extension due to the Pandemic. For more details, visit the website.

Figure 37. Pictures of the attendants to the AQUALITY final meeting in Ioannina (Greece).

Photo-irradiationand Adsorption based Novel Innovations for Water-treatment, PANIWATER

Participants: Royal College of Surgeons in Ireland, National Environmental Engineering Research Institute, Universidad Rey Juan Carlos, Birla Institute of Technology & Science society-bits, National University of Ireland Maynooth, Society for Development Alternatives, INNOVA SRL, Kwality Photonics P Ltd, CIEMAT, Auroville Foundation/ASSA/Affordable Water Solutions, University of Cyprus, University of Ulster, Institute of Technology SLIGO-ITS, AGUASOIL, SRL, Universita de Salento, Buckinghamshire new University, Universidad de Santiago de Compostela, Society for Technology & Action for Rural Advancement.

Contact: Isabel Oller, isabel.oller@psa.es

Funding agency: European Commission, H2020-SC5-2018-1 (GA 820718)

Background: About 2.1 Billion people live without access to safe water sources. Contaminants of Emerging Concern (CECs) such as pharmaceuticals, personal care products, pesticides and nanoparticles are increasingly being detected in wastewater and in drinking water around the world, in addition to geogenic pollutants, pathogens, antibiotic resistant bacteria and antibiotic resistance genes. Water treatment systems that remove CECs and common contaminants from wastewater and drinking water are therefore urgently needed.

Objectives: PANIWATER will develop, deploy and validate in the field six prototypes for the removal of contaminants, including CECs, from wastewater and drinking water. The prototypes for wastewater treatment will consist of (i) a 20,000 L/day multifunctional oxidation reactor, (ii) a 10 L/day photoelectrochemical system, and (iii) a 100 L/day solar photolytic plant. The prototypes for drinking water treatment will consist of (iv) a 300 L/hour filtration, adsorption, and UVC LED system (v) a 20 L transparent jerry can for solar water disinfection, and (vi) a 2,000 L/day electrocoagulation, oxidation, and disinfection t system.

Achievements in 2022: The annual general assembly meeting of the PANIWATER project took place on the 3rd and 4th May 2022 in Lecce (Italy). The University of Salento (Italy), partners of the project, organized this meeting including a visit to the municipal wastewater treatment plant in Fasano, where the pilot plant with the MITOX technology is already in operation. In addition, on May 5th 2022, a workshop focused on Photo-irradiation and Adsorption based Novel Innovations for Water-treatment in the frame of PANIWATER general assembly was celebrated. Maria Jesús Abeledo, post-doc working in the Solar Treatment of Water Unit at PSA, presented the latest results on the simultaneous elimination of pathogens and microcontaminants contained in actual effluents of municipal wastewater treatment plants by combining solar energy with oxidants such as peroxomonsufate. The steering committee of the PANIWATER project took place on 29th and 30th November 2022, as a hybrid event, attendants met at the University of Santiago de Compostela (Spain). At that meeting, the latest experiments and ecotoxicity tests of jerry can prototypes were decided as well as the DEMO sites already installed or in progress where presented. In Figure 38, the 3D diagram of the UV/PV system almost finished in Neeri, India, is shown. In addition, the non-cost one year extension of the project to mainly demonstrate the feasibility of the technology for urban wastewater regeneration to be reused in crops irrigation has been approved until the end of January 2024. For more details visit the website.

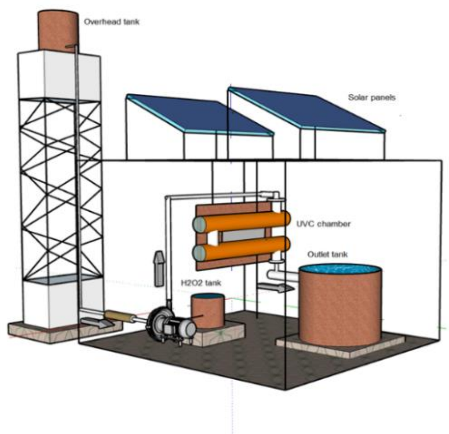

Figure 38. 3D diagram of the SPP system to be installed as DEMO plant in India to regenerate effluents from secondary treatment with UV/H_2O_2

Advanced and hybridized technologies addressing recalcitrant pollutants, micropollutants, reusing and revalorization in different wastewater, including technological and economical approaches. (CALYPSOL)

Participants: UPV, URJC, CIEMAT.

Contact: Sixto Malato, sixto.malato@psa.es

Funding agency: Spanish Ministry of Science, Innovation and Universities (Reference RTI2018-097997-B-C32)

Background: The project tries to put together the know-how in different areas of AOPs and wastewater decontamination, to be a step forward to solve real problems of our society by designing new strategies for the treatment of complex wastewaters, soil washing, or hydrogen generation adapted to southern/sunny countries, which can be, in turn, employed for other technological applications. The goals of the project are also thought to enhance the scientific and technological competitiveness of the Spanish productive system in the field of environmental remediation in connection with renewable source of energy.

Objectives: CALYPSOL will apply different reductive processes in order to obtain valuable by-products, such as hydrogen, to investigate the oxidative capability of different Advanced Oxidation Processes for urban wastewater (secondary effluents) disinfection, the oxidative capability of photocatalytic processes with semiconductors and zero-valent iron (ZVI) materials, combination/integration of advanced technologies (AOPs and separation processes such as Membrane Distillation, NF, UF, etc.) for solid and wastewater treatment and resource recovery, disinfection and abatement of CECs in urban wastewater using solar or UVC based treatments in combination with primary (mainly solid separation) and secondary treatments (biotreatment). The final goal is to assess the technical feasibility of each process and the overall costs to compare with BATs available in northern Europe and propose alternatives for southern sunny countries.

Achievements in 2022: This national project officially finished on 30th September 2022, after a 9 month non-cost extension approved by the Spanish Research Agency due to delays in some activities provoked by the Pandemic situation. A coordination meeting took place on 9th and 10th March 2022 in Aranjuez (Spain), in which the main achievements of the last 6 months were discussed and the activities and tasks to be finalized until the end of the project were clearly defined. The last project meeting took place in Riopar (Spain) on 7th and 8th September 2022. The main conclusions that were presented in the meeting as final summary of the results obtained in this national project were: a) reducing and oxidative processes have been coupled, b) reduction has been used to generate hydrogen, c) oxidative processes have been applied to regenerate secondary effluents from municipal wastewater treatment plants (with simultaneous elimination of CEC, ARB and ARG), as well as for the decontamination of industrial and agricultural wastewater, d) new solar photocatalysts have been obtained, e) the detoxification of effluents has been evaluated, f) combined separation and oxidation technologies for the revaluation and remediation of water and g) economic and LCA studies have been carried out. As a sample of some of the results obtained in this project, in Figure 39, the performance of different zero valent iron photocatalysts were tested for the elimination of some well-known contaminants.

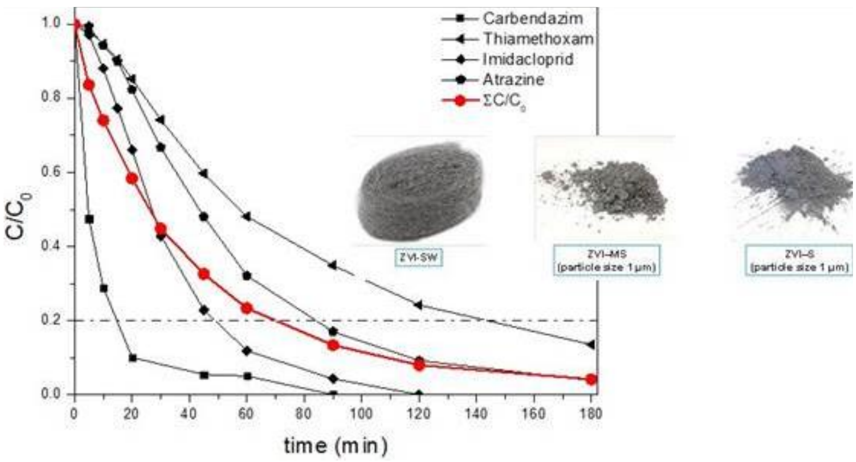

Figure 39. Microcontaminants degradation with 1 mM of $S_2O_8^{2-}$ at neutral pH. Experimental conditions: C0=100 µg/L (each) and ZVI-MS = 55.8 mg/L

Towards increasing the sustainable treatment and reuse of wastewater in the Mediterranean Region, AQUACYCLE

Participants: CERTH, CIEMAT, IRM, HCWW, CERTE INGREF.

Contacts: Isabel Oller, isabel.oller@psa.es

Funding agency: European Commission, ENI CBC Mediterranean Sea Basin Programme 2014-2020. Thematic objective B.4, Priority G.4.1 (A_B.4.1_0027)

Background: Reclaimed municipal wastewater is considered a valuable non-conventional water resource. Especially in water scarce regions of the Mediterranean, the use of non-conventional water resources to complement or replace the use of fresh water resources provides multiple benefits in terms of supporting the local economy (e.g. in irrigated agriculture), improving the living standards of societies, reducing the pressures on natural resources and addressing climate change challenges.

Objectives: AQUACYCLE aspires to change the paradigm of viewing wastewater as an unsafe effluent, to that of an abundant all-year-round resource that has multiple uses. Our eco-innovative APOC technology, which combines anaerobic digestion (above, left), Photocatalytic Oxidation and a Constructed wetland, is set to capture the imagination of professionals and the public alike. Our hybrid set up not only augments water supply all year round but also produces biogas and fertilizer, setting a good example for the circular economy. It will create new, thriving biodiversity habitats as a visible climate change mitigation measure. In addition, but not least, it operates on solar energy, ensuring a low cost of operation.

Achievements in 2022: The 1st and 3rd March 2022 the sixth coordination meeting of AQUACYCLE project took place virtually within the motto “Revisiting our strategy to reach all our targets: timeframe required to complete all upcoming activities and timing of the associated financial expenditures”. Main task considered in this meeting was the preparation of a major amendment asking for a non-cost extension of the project of one year due to the delays on the tenders of Lebanon and Tunisia for the construction of the APOC demo system in their selected locations. The Solar Treatment of Water Research Unit organized the second series of workshop at PSA, on 25th March 2022 with the focus on “Action plans for the regeneration of treated wastewater”. At this workshop, experts from ESAMUR (Murcia) and the Provincial Council of Almería, explained the situation of Murcia and action plans to be implemented in Almería trying to follow the model of Murcia in leading wastewater reuse in Europe. Seventh coordination meeting was held also virtually on 26th September 2022 within the motto “Towards achieving our goals in the last year of project implementation”. At this meeting, the Solar Treatment of Water Research Unit presented the first results obtained from its facilities, at pilot scale, on the elimination of microcontaminants and pathogens contained in the outlet of the wetlands at the MWWTP of Blanca in Murcia. In Figure 40, a picture of the wetlands and the raceway pond reactor installed as demo site in Blanca are shown. For more details visit the website.

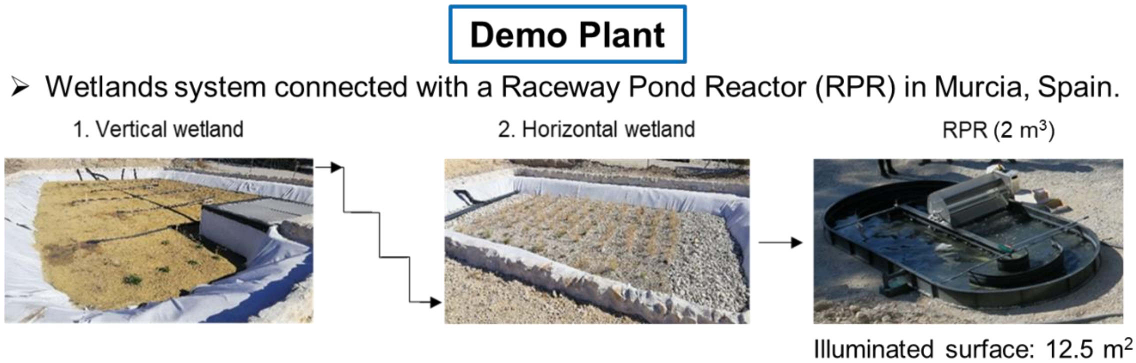

Figure 40. Demo plant constructed in the MWWTP in Blanca, Murcia. The vertical wetland is directly connected to the outlet of an anaerobic reactor (APOC technology).

ENERGy access and green transition collaboratively demonstrated in urban and rural areas in AfrICA (ENERGICA)

Participants: Technische Universitat Berlin, United Nations Environment Programme, Universite Abdou Moumouni de Niamey, Norges Teknisk-Naturvitenskapelige Universitet, Trialog, Finergreen Africa, Hudara GGMBH, Association Energy Generation, Ecowas Centre for Renewable Energy and Energy Efficiency, Fundacion Tekniker, Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, RISE Research Institutes of Sweden, The Waste Transformers Nederland, Freetown Waste Transformers, Ecosun innovations, Arenys Inox, Nanoe Madagascar, SADC Centre for Renewable Energy and Energy Efficiency, Association Africaine pour l electrification rurale (cluber), East African Centre of Excellence for Renewable Energy and Efficiency, The Kenya Power and Lighting Company, Odit-e, Hive Power, Opibus, Stima sas, Untapped Water Limited, Jokosun, Euroquality.

Contact: M. Inmaculada Polo, inmaculada.polo@psa.es

Isabel Oller, isabel.oller@psa.es

Funding agency: Horizon 2020 - Research and Innovation Framework Programme (H2020-LC-GD-2020-1)

Background: Green transition is at the forefront of political and societal ambitions for more sustainable economies, industries, and societies. The means to reach green transition usually consider Renewable Energy Technologies as the key towards CO2 emission reduction and decarbonisation of the electricity grid. However, sustainable uptake of RETs can only be ensured through the effective implication of stakeholders all along the value chain and throughout the development of tailored technologies. In this context, the ENERGICA project focuses on a wider scope of activities than strictly technical, providing sustainable technologies.

Objectives: The main objective of ENERGICA is to demonstrate the efficient implementation of renewable energy technologies to match local contexts' needs. To do so, three different demonstration sites will rely upon local Energy Transition Boards, which will manage community-scale Integrated Community Energy Systems. Based on these methodologies and respective innovative technologies, ENERGICA will demonstrate positive social, environmental, technical, and economic impacts from the high-energy efficiency and low carbon emission renewable energy technologies. The main role of CIEMAT in this project is related to the implementation of water treatment solar-based solutions in two different countries: Madagascar and Sierra Leona.

Achievements in 2022: During this year, several new and novel photocatalytic materials developed and immobilized on different substrates have been tested by CIEMAT. The materials were based on TiO2 immobilized on three supports, aluminium (at 100 g/L of catalyst), stainless steel (at 100 and 200 g/L) and epoxy (at 10 and 20 % of catalyst load) (Figure 41). The water purification performance has been addressed by using *Escherichia coli* (at 10^6 CFU/mL initial concentration) as a model of bacterial indicator and sulfamethoxazole (SMX) (Antibiotic) and imidacloprid (IMD) (Insecticide) as models of contaminants of emerging concern (at 100 μg/L of initial concentration). Besides, total organic carbon, turbidity, pH, conductivity and transmittance of the water were simultaneously monitored. Dark and solar tests carried out at a laboratory scale demonstrated that the best catalyst performance for water purification was obtained by 200 mg/L of TiO_2 immobilized onto stainless steel material, maintaining its performance along several cycles of materials use (Figure 41).

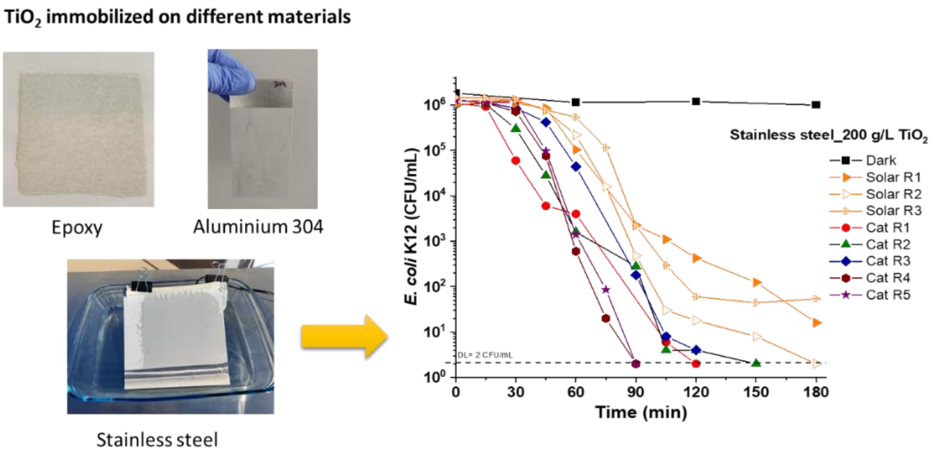

Figure 41. Tested materials at CIEMAT-PSA containing TiO_2 immobilized (left) and *E. coli* inactivation profiles obtained by Stainless steel_200 mg/L of TiO_2 in the dark, under natural sunlight and in comparison with solar-only disinfection.

Urban wastewater reclamation by Novel mAterials and adVanced solar technologies: assessment of new treatment quAlity Indicators, NAVIA

Participants: Universidad de Almería, CIEMAT (Plataforma Solar de Almería), Universidad Politécnica de Valencia.

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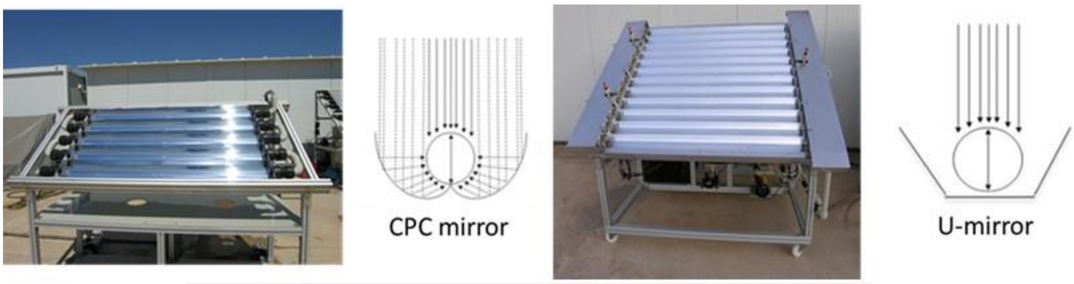
Funding agency: Ministerio de Ciencia e Innovación. Proyectos de I+D+I «Retos Colaboración» 2019 (Reference: PID2019-110441RB)

Background: Wastewater reclamation is currently a reality with many advantages for the environment and human well-being. Nevertheless, it´s still requiring investigating practical aspects to enhance the correct management and implementation of the different novel technologies currently available (such as those using renewable sources of energy, like solar energy), with the purpose of selecting the best treatment technologies based on high efficiency, low energy, low cost and low or null chemical and microbiological risks.

Objectives: The NAVIA project aims to develop new technologies based on solar advanced oxidation processes for urban wastewater (UWW) reclamation. The following research areas will be covered along the project execution: synthesis of novel photocatalysts active under natural solar radiation, kinetics studies (modelling mechanistic degradation pathways) of new microbial pathogens (coliphages and antibiotic-resistant bacteria and genes (ARB and ARG)) and organic microcontaminants (OMCs) as treatment quality indicators at laboratory and pilot scale, the assessment of solar AOPs at pilot plant scale in batch and continuous flow mode and the development of a making-tool system based on water quality monitoring for UWW reclamation.

Achievements in 2022: During this year, the simultaneous capability for water disinfection and decontamination of different solar photocatalytic and photochemical treatments, including photo-Fenton with EDDHA as an iron chelate, H_2O_2 alone, peroxymonosulfate (PMS) and persulfate (PS) alone, have been investigated at pre-selected optimized reagent concentrations. The capability performance has been investigated using actual secondary effluent from the UWW treatment plan of El Bobar (Almeria, Spain), at the pilot plant scale in a solar Compound Parabolic Collector (CPC) reactor. The following water targets were monitored along the treatment time: contaminants of emerging concern (trimethoprim, Sulfamethoxazole and pyrimethanil spiked at an initial concentration of 100 µg/L), microbiological targets naturally occurring on UWW (*E. coli*, coliforms and coliphages), ARGs (16S RNA, *Sul1, intl1, qnrS Tet(E), blaTEM*), as well as other parameters such as reagents concentration, organic content and water temperature.

All these tests and operational conditions have been investigated at the pilot plant scale in two different solar reactors: (i) a Compound Parabolic Collector (CPC) reactor and (ii) a V-trough mirror reactor, which main differences are the photo-reactor tube diameter and the mirror shape with the objective of performance comparison (Figure 42). The results obtained in this study demonstrated the success capability of these treatments at the pilot plant scale for UWW reclamation at both types of solar reactors.



	CPC reactor	V-mirror reactor
Total Volume	10 L	100 L
Illuminated volume	5 L	75 L
Illuminated area	0.44	2 m^2
Total number of tubes	2	12
Tube diameter	50 mm	75 mm
Tube thickness	2.2 mm	2.2 mm

Figure 42. Images and main characteristics of the solar CPC photo-reactor and V-trough mirror reactor used for UWW reclamation by solar photochemical treatment at pilot plant scale located at CIEMAT facilities.

Revalorization of acids and heavy metals in waste streams from surface treatments with membrane technologies, ELECTRONÍQUEL.

Participants: CIEMAT (Plataforma Solar de Almería), Electroníquel S.A..

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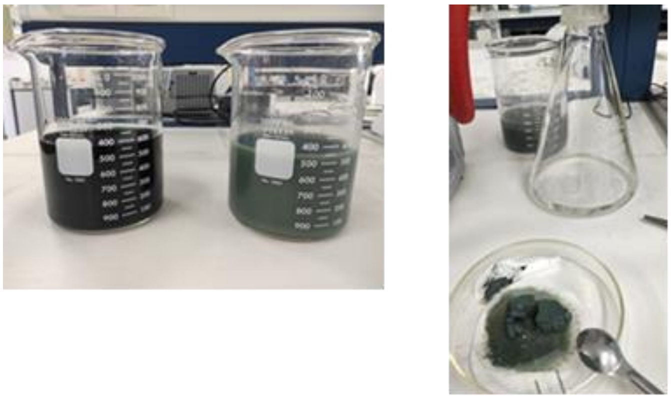
Funding agency: European Regional Development Fund-Instituto de Desarrollo Económico del Principado de Asturias (IDEPA) 2020 (Reference: IDE/2020/000398).

Background: With the development of this project, the intention is to transform the waste generated in the coating processes of metal pieces, mainly in the pickling solution and passivation stages, into raw materials for the process itself, reducing the consumption of natural resources and carbon dioxide emissions based on principles of circular economy. Diffusion dialysis and membrane distillation will be validated for applications of great interest in the metal coating industry.

Objectives: The objectives pursued with this project are: i) adaptation of a combined treatment system for the revaluation of waste streams from an electrolytic zinc plating process, specifically from the pickling and passivation stages; ii) reduction of water consumption in the zinc plating process by regeneration the exhausted baths; iii) recovery of acids and metals from waste streams. The decrease in the consumption of raw materials in the process is expected by 15 %; iv) validation of the technologies used with real samples from the production chain.

Achievements in 2022: This project and the service contract signed with the company finished in May 2022. Corrosion tests in artificial atmospheres-saline mist have been carried out. The influence of the method used for the removal of contamination in corrosion resistance has been studied. Precipitation conditions were obtained and are shown in Figure 43. The membrane distillation pilot plant, installed at CIEMAT's facilities, has been used for the treatment of the passivation solution for the production of demineralized water and the regeneration of the waste solution. A few problems with the pilot plant arose at that moment: Breakage of the crystallizer and leaks, and module leakage. In the case of the module, optimization of the thickness of the vitons and their replacement was carried out.



Sample	$[CrO_3]$ (g/L)	$[Zn^{2+}]$ (g/L)	$[Fe^{2+}]$ (g/L)
Exhausted bath	5.9	2.75	2.10
pH=5	5.4	2.04	1.25
pH=5.5	4.7	1.50	1.20

Figure 43. Precipitation conditions studied in the ELECTRONÍQUEL project and service contract with the Solar Treatment of Water Research Unit.

Solar catalysis for a renewable energy future, SOLFUTURE

Participants: Fundación IMDEA Energia, Instituto de Ciencia de Materiales de Madrid-CSIC, Fundacio institut catala D'investigacio quimica (ICIQ), PSA-CIEMAT, APRIA Systems, S.L., Compañia española de petroleos S.A. (CEPSA).

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Funding agency: Proyectos de I+D+i en líneas estratégicas, en colaboración público-privada, del programa estatal de I+D+i orientada a los retos de la sociedad (Ref. PLEC2021-007906).

Background: The implementation of new systems to produce sustainable fuels and chemicals by the integration of renewable energy sources is one of the major challenges for our society. SOLFuture proposes two new concepts of photoreactor prototypes for the generation of value-added products and fuels (H_2, CH_4, C_2+, NH_3 and chemical platforms).

Objectives: A combined strategy based on two complementary approaches has been designed: (i) the development of photocatalytic technologies based on the production of H_2 from waste water and biomass as reductant in liquid and gas phase using hybrid organic/inorganic heterojunctions based on metal oxides and conjugated porous polymers; (ii) a photo(electro)chemical cell formed by organic/inorganic heterojunctions in their thin-film form, and a PV-EC photoanode, made by the coupling of an organic solar cell and a highly active porous anode decorated with co-catalyst nanoparticles.

Achievements in 2022: The main goal of PSA was to explore pilot-scale combination of H_2 generation with simultaneous water disinfection or decontamination. Performance of a TiO_2-CuO mixture and NiO:TiO_2 mixture has been tested. It has been demonstrated that using commercial semiconductors it is possible to attain similar solar to hydrogen efficiency to that described with synthetic photocatalysts.

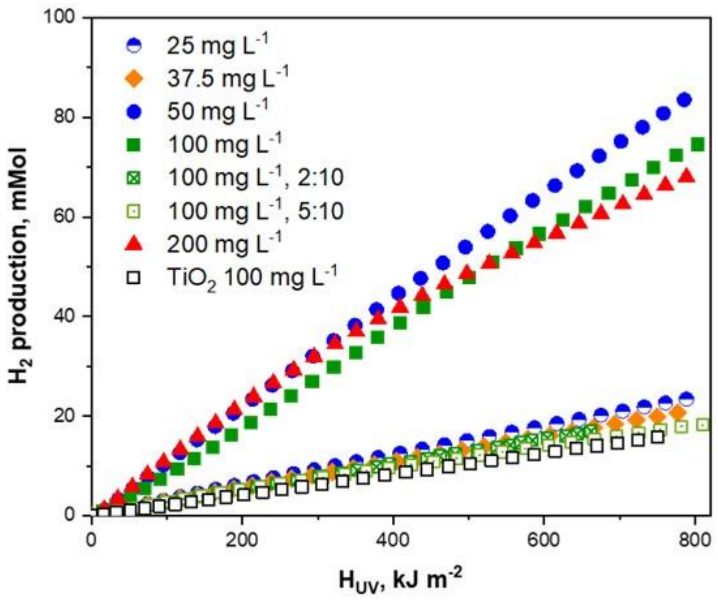

Figure 44. Photocatalytic H_2 generation at different $NiO:TiO_2$ concentrations and ratio, in water. TiO_2 alone is also shown. Reaction conditions: $NiO:TiO_2$ 1:10, glycerol = 0.075 M.

Revalorisation of wastewater through technologies that improve the water-renewable energy-food nexus, AQUAENAGRI

Participants: Universitat Politècnica de Valencia, Universidad Rey Juan Carlos, Plataforma Solar de Almería

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Funding agency: Proyectos de Generación de Conocimiento en el marco del Programa Estatal para Impulsar la Investigación Científico-Técnica y su Transferencia, del Plan Estatal de Investigación Científica, Técnica y de Innovación, 2021-2023 (Ref. PID2021-126400OB-C33)

Background: Improve the quality of the effluents involved in aquaponics, as well as regenerated water to be used as an influent. For this purpose, it is necessary to monitor micropollutants, heavy metals, microplastics, antibiotics and pesticides removal, the inactivation of antibiotic-resistant bacteria (ARB) and the effect on the antibiotic-resistant genes (ARG).

Objectives: Investigating the advanced oxidation process for polishing regenerated water from MWWTP to be used in aquaculture, solar photocatalytic hydrogen production using the organic content of WWTP, aquaculture and hydroponic effluents as a sacrificial agent, evaluation of the applied processes for pathogens elimination in aquaculture and hydroponic inlets, development of materials with high photocatalytic performance under solar radiation.

Achievements in 2022: The increase in water use efficiency of aquaponics will be based on sustainable water treatment for water reuse either within the same aquaculture system or for direct crop irrigation depending on country regulations. Polishing water treatment will be based on either photovoltaic-electricity powered UV-C LED, UV-A LED, simulated solar radiation or the use of solar CPC and Raceway Pond Reactors (RPRs), which can also be made of low-cost reflectors to increase solar light collection and materials, respectively. Photovoltaic-electricity powered UV-C LED, solar CPC, and RPR technologies will be tested in combination with a low dosage of chlorine (< 10 mg/L) to increase disinfection and ARG/CEC removal efficacy. Initial research and small-scale prototypes will be tested. Project has just begun on September 1st, 2022.

Towards Digital Transition in Solar Chemistry: Photoreactors, SOLARCHEM 5.0

Participants: IMDEA Energy, ALBA-CELLS, Instituto de Ciencia de Materiales de Madrid -CSIC, Institute of Computational Chemistry and Catalysis - Univesity of Girona, Instituto de Química Física "Rocasolano"- CSIC, PSA-CIEMAT, Instituto de Ciencia de Materiales de Sevilla -CSIC, Universidad Politécnica de Madrid, Universidad Rey Juan Carlos

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Funding agency: Proyectos orientados a la transición ecológica y a la transición digital, programa estatal para impulsar la investigación científico-técnica y su transferencia, del plan estatal de investigación científica, técnica y de innovación 2021-2023 (Ref. TED2021-130173B-C43)

Background: EU is immersed in an unprecedented ecological transition based on the increase of efforts to develop sustainable technologies aiming to achieve a climate neutrality towards a low-carbon economy. The development of technologies, Earth-abundant resources and wastes as raw materials, entail a breakthrough in the chemistry, energy production and storage industries. Moreover, the EU is also embarking on a transition towards digital leadership being a priority to place the research and innovation in Artificial Intelligence at the service of a sustainable industry.

Objectives: SolarChem 5.0 aims to develop Artificial Intelligence powered Solar photoelectrochemical technologies based on hybrid bio-based materials and efficient reactors that use Earth-abundant resources and waste as raw materials. R&D efforts are focused on: (1) Development of novel chemically stable hybrid photoelectrodes; (2) Highly active, selective, and long duration bio-based catalysts; (3) Optimized reactor design and upscaling; (4) Diversification of the considered feedstock; (5) Implementation of AI and Machine learning tools to achieve the development of autonomous Solar chemistry technologies; and (6) To advance on an appropriate standardized methodology and Adoption of Open Science practices

Achievements in 2022: SolarChem 5.0 will pave the way to the new era of the Chemistry-Digital nexus, making a potential alternative to unsustainable chemical industry and fossil-based energy sources. SolarChem 5.0 will lead towards the next generation of Artificial intelligence powered Solar chemistry technologies converting Earth abundant resources and waste feedstock into fuels and chemicals, replacing fossil fuels as the main energy and chemical feedstock. SolarChem 5.0 as whole will lay the basis of a radical new strategy for the digital-ecological transition and signify a wide range of future returns in terms of societal or economic innovation or market creation. Project has just begun on December 1st, 2022.

Towards the improvement of the Urban Water Cycle Resilience: Assessment of Solar Water Reclamation Technologies focused on Disinfection by-products, Antibiotic Resistant bacteria and Genes elimination, DIGIT4WATER

Participants: CIEMAT-PSA (coordinators), UPM and CIMNE

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Funding agency: Proyectos orientados a la transición ecológica y a la transición digital, programa estatal para impulsar la investigación científico-técnica y su transferencia, del plan estatal de investigación científica, técnica y de innovación 2021-2023 (Ref. TED2021-129969B-C31)

Background: Treated wastewater reuse can be considered a reliable water supply, quite independent from seasonal drought and weather variability and able to cover peaks of water demand, especially in water-scarce areas. Wastewater reuse for irrigation in agriculture is by far the most established end-use for reclaimed water in low-income countries as well as in arid and semi-arid ones. In countries of higher income level, concerns tend to shift from microbial risk to organic microcontaminants (OMCs) such as pesticides, pharmaceuticals, illicit drugs, synthetic and natural hormones, personal care products, disinfection by-products (DBPs), and Antibiotic Resistance Elements (i.e. antibiotic resistant bacteria and genes (ARB&ARGs)). Conventional treatment trains in Municipal Wastewater Treatment Plants (MWWTPs) are poorly effective to remove OMCs, constituting a particular concern when effluents are reused for crop irrigation. In parallel, digitalization of the water sector requires adopting a common data platform for data valorisation and information sharing, supporting smart quantitative water management and conservation through monitoring, and improving transparency and data sharing within the water sector and the public to promote multidisciplinary cooperation.

Objectives: The DIGIT4WATER project addresses the improvement of the resilience and digitalization aspects in municipal water management and treatment systems, and the circular economy concept including the potential deployment of renewable energies, in order to contribute to the environmental objectives of the ecological and digital transitions collected in the EU Regulation 2020/852 of the European Parliament and the Council. DIGIT4WATER will cover various recognized environmental challenges: adaptation to climate change; sustainable use and protection of water and marine resources; and transition to a circular economy.

Achievements in 2022: The DIGIT4WATER project aims to be the starting point on digitalization of the urban wastewater treatment and management sector. This challenge will be addressed by the development of a decision and technology design support tool based on machine learning models. Such models, will require to be fed by a vast amount of data which are programed to come from three sources: (i) actual physicochemical data of urban raw wastewater and secondary and tertiary treatment effluents from several MWWTPs already committed with the project from the south and the center of Spain; (ii) monitoring of organic microcontaminants (OMCs) and disinfection byproducts (DBPs) as well as pathogens, antibiotic resistant bacteria and antibiotic resistant genes (ARB & ARGs) present in the same raw wastewaters and effluents; (iii) laboratory and pilot scale alternative tertiary treatments based on UVC and solar technologies applied on actual MWWTPs secondary effluents for the elimination of OMCs and inactivation of pathogens, ARB & ARGs aiming to comply with the new European Regulation on water reuse (2020/741) with the certainty of non-generating DBPs.on. Project has just begun on the 1st December 2022.

Monitoring and diagnosis of the purification, purification and regeneration of urban water in regions with water stress and development of alternative sustainable treatments to chlorination, MODITRAGUA

Participants: University of Almería (CIESOL), CIEMAT-PSA, Council of the Province of Almería.

Contact: Isabel Oller, isabel.oller@psa.es

Funding agency: Convocatoria de subvenciones a «proyectos de I+D+i» universidades y entidades públicas de investigación (BOJA n.º239, de 15 de diciembre de 2021). Proyectos de investigación orientados a los retos de la sociedad andaluza (Ref. ProyExcel_00585)

Background: Climate change poses a clear threat to humanity and water is the key factor on which achieving true sustainable development will depend. Spain is one of the most vulnerable European countries to the impact of climate change as it suffers from high levels of water stress. 20 % of its territory can already be considered desert and between 75 % and 8 0% is at risk of desertification. In addition, very important activities for our economy, such as agriculture or tourism, are intensive in water consumption.

Objectives: The general objective of MODITRAGUA is to propose solutions to face the challenges of the urban water cycle, which would make building more resilient cities through sustainable management of water resources possible. The specific objectives that will be addressed in MODITRAGUA are: (i) Definition of the sampling and monitoring plan in different ERAR and PAAP in the province of Almería; (ii) Analysis of physical-chemical parameters and identification of contaminants: massive screening of contaminants of emerging concern (CEC) and disinfection by-products (chlorination) (DBP); (iii) Analysis of microbiological parameters: bacteria and viruses considered in the new regulation of the European Parliament on reuse and the draft of the drinking water supply regulations; (iv) Proposal and evaluation of alternative treatments to chlorination in ERAR and PAAP; (v) Analysis of the monitoring plan and development of a Computer Decision Tool based on machine learning techniques. The project has just begun in December, 2022.

Building energy performance assessment based on in-situ measurement, analysis and simulation, In-Situ-BEPAMAS

Participants: CIEMAT.

Contacts: María José Jiménez, mjose.jimenez@psa.es

Funding agency: Spanish National Research Agency (Agencia Estatal de Investigación). Call: “Proyectos de I+D+i del Programa Estatal de I+D+i Orientada a los Retos de la Sociedad 2019”. Project reference PID2019-105046RB-I00.

Background: Reliable procedures for building energy performance assessment are essential for: 1. Evaluation of deviations regarding design specifications in as-built new buildings. 2. Comparison to reference values in pre-rehabilitation diagnosis. Most currently used compliance checks based on simulations can deviate significantly from reality. This performance gap must be addressed by research.

Objectives: Application of inverse modelling techniques, assisted by sensitivity analyses applying dynamic simulation tools, to the development of reliable, cost-effective and non-intrusive experimental methodologies, for the in-situ energy performance assessment of the whole building envelope, with applicability to in use-buildings when construction characteristics of buildings are not available or incomplete

Achievements in 2022: The research conducted at the LECE Laboratory at PSA and also using stock data previously gathered here, delivered the following in 2022:

The findings of the Coheating conducted in 2021 in the Single-zone building at the LECE Laboratory were published in a scientific journal (Energy and Buildings 2022, 266, 112140). This paper highlighted the need of further research to address the performance gap between the experimentally obtained and the theoretically assessed energy performance parameters. To support such further research three additional Coheating test campaigns have been launched in 2022: Two test campaigns in the same Single-zone building at the LECE Laboratory in January and December 2022, and one test campaign in an office of the ARFRISOL Building Prototype at PSA.

The measurement of the CO2 concentration has been identified as one of the measurements that plays a key role in the development of cost effective and non-intrusive procedures for the experimental assessment of occupancy patterns and air renovation rates in in-use buildings. However, these applications are hampered by problems usually shown by these sensors such as typical offset, drift, and oscillations in the measurements that are not related to actual changes in the CO2 concentration. An in depth analysis considering a long term test campaign (fourteen years) and two specific test bench marks have been conducted (Figure 45 a). Several sets of sensors distributed in different rooms of the ARFRISOL building prototype have been included in the long term study (Figure 45b). A paper has been published describing this work and some recommendations to skip the usual problems when these sensors are used (Sensors 2022, 22(23), 9403).

Advanced RC models have been applied to obtain the Heat Transfer Coefficient (HTC) of a Round Robbin Test Box and a room in the ARFRISOL In-Use Office Building Prototype. The influence of the different meteorological and use conditions on the accuracy of the HTC estimates has been analysed.

(a) (b)

Figure 45. (a) CO_2 sensors installed in the benchmark set up, (b) CO_2 sensors built-in in the ARFRISOL building prototype.

11 The European Solar Research Infrastructure for Concentrated Solar Power, EU-SOLARIS

The European Solar Research Infrastructure for Concentrated Solar Power (EU-SOLARIS) is a world-class distributed research infrastructure to be set up as a central hub responsible for the coordinated operation of national research centres in Concentrating Solar Power/Solar Thermal Energy (CSP/STE) technologies, which shall dedicate part of their research and development capacities to sharing contents, tools and know-how related to these CSP/STE technologies. It aims to achieve a real coordination of Research and Technology Development (RTD) capabilities and efforts in CSP/STE technologies by the European Research Centres. EU-SOLARIS will become the reference for CSP/STE and maintain Europe at the forefront and leadership of these technologies by providing the most complete, high quality scientific portfolio and facilitating the access of researchers to highly specialised facilities via a single-entry point. EU-SOLARIS will link scientific institutions, academia and industry and speed up the development of research and innovation due to a closer collaboration model, knowledge exchange management and a wider dissemination of results. It will increase the efficiency of the economic and human resources required to achieve excellence and provide efficient resources management to complement research and avoid redundancies, when identifying new requirements for the improvement of the research facilities, and for the construction of new ones (when needed), and it will optimize and promote the specialization of existing ones.

EU-SOLARIS is supported by its member countries Cyprus, France, Germany, and Spain, with national funds. When the legal entity is launched, Portugal will participate as an observer.

EU-SOLARIS has been formally approved in 2022 as an ESFRI entity to become the European reference with regard to research infrastructures in Concentrating Solar Thermal and Solar Chemistry Technologies. This ERIC (European Research Infrastructure Consortium) organization has the objective to reinforce the collaboration between scientific institutions and industry by coordinating, as a unique infrastructure of distributed character, the main installations of R&D also offering a single contact point where facilities, resources and research services will be effectively offered to users demanding the services. The official announcement was made by the European Commission on October 20th at the International Conference on Research Infrastructures, ICRI 2022 (Brno, Czech Republic, October 19-21). EU-SOLARIS statutes were published in the Official Journal of the European Union on the 24th of November 2022. Initial members of the initiative are Spain (coordinator), Germany, France and Cyprus, plus the addition of Portugal as an observer.

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Figure 46. Image of the new website being developed for this EU-SOLARIS ERIC.

12 Training and educational activities

The ruling principle of the PSA's training program is the creation of a generation of young researchers who can contribute to the deployment of solar thermal energy applications. Through this program, about twenty students of different nationalities are admitted each year so that we can transmit the knowledge in solar thermal technology accumulated at the PSA throughout its over forty years of experience to new generations of university graduates.

The main features of this training program are:

- Management of the Ph.D. fellowship program in association with the University of Almeria (UAL) and with the own program to young researcher of CIEMAT.
- Management of miscellaneous educational cooperation agreements with other entities for sending students to the PSA (Universities of Almería, Polytechnic of Madrid, Autónoma of Madrid, Santiago-Chile, Gabes-Tunisia, Brescia-Italy, Karlsruhe Institute of Technology-Germany, TH-Köln-Germany, IES Los Angeles, CPD MEDAC,etc)

The close and enduring collaboration between CIEMAT and the University of Almería has allowed us to carry out the fourth edition of the Official Master's in Solar Energy (60 Credits). The hallmarks of this course, along with its quality, make it an attractive proposition for students, both Spanish and from other countries, who want to gain a first-rate qualification in the field of solar energy and its many applications. The Masters in Solar Energy allows its graduates to deepen in the different technologies and applications that currently exist for solar energy.

The SFERA-III project, coordinated by CIEMAT, addresses advanced science challenges and integrated research activities in the field of Concentrating Solar Thermal (CST) by integrating key European research infrastructures into an ambitious wide project aiming to offering the R&D community a new level of high-quality services. In this context, this project is coordinating efforts to train researchers and engineers on CST technologies. Among the networking activities carried out within the framework of this project are an annual seminar for Ph.D. students from the SFERA-III Consortium (Doctoral Colloquium) and a summer/winter school open to the research community.

The 4^{th} Doctoral Colloquium, restricted to SFERA-III members, was held on 11^{th} and $12t^{h}$ September 2022 in Cologne (Germany). Afterward, SFERA-III Summer School (open to a large audience and organized in hybrid mode) was hosted at the same location on 14^{th} and 15^{th} September and it was focused on "Smart CSP: how smart tools, devices, and software can help improve the design and operation of concentrating solar power technologies".

In order to promote the higher education of young researchers in the environmental applications of AOPs, as well as to overcome national boundaries and bureaucracy barriers, a group of European scientists (Management Committee, MC) from different Universities and Research Institutes with a strong and internationally recognized expertise in this field, founded (June 2014) the "European PhD School on Advanced Oxidation Processes". The PSA is one of the members of this school since its creation.

13 Facilities and Infrastructure

Facilities associated with Line-focus solar concentrators

The DISS experimental plant

This test facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure - high-temperature (100 bar/400°C) steam in parabolic-trough collector absorber tubes. It was the first life-size facility built in the world where two-phase-flow water/steam processes in parabolic-trough collectors could be studied under real solar conditions.

The facility (see Figure 47 and Figure 48) consists of two subsystems, the solar field of parabolic-trough collectors and the balance of plant (BOP). In the solar field, with the upgrade implemented in 2012, feed water is preheated, evaporated and converted into superheated steam at a maximum pressure of 100 bar and maximum temperature of 500°C as it circulates through the absorber tubes of a 1000-m -long row of parabolic-trough collectors with a total solar collecting surface of 5400 m^2. The system can produce a nominal superheated steam flow rate of 1 kg/s. In the balance of plant, this superheated steam is condensed, processed and reused as feed water for the solar field (closed loop operation).

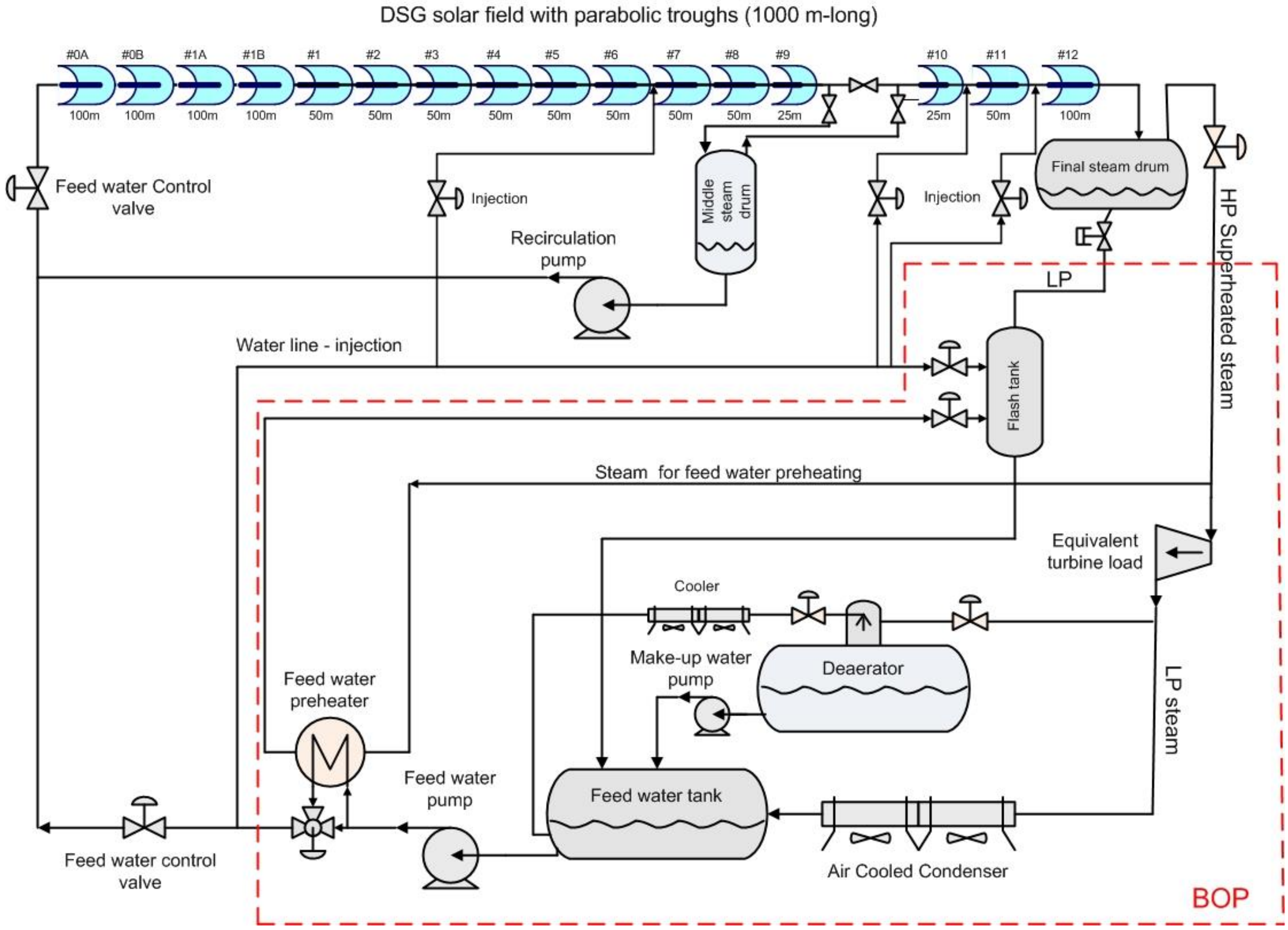


Figure 47. Simplified flow diagram of the PSA DISS loop.

Facility operation is highly flexible and can work from 30 bar up to 100 bar. It is also equipped with a complete set of valves allowing the solar field to be configured for Recirculation (perfectly differentiated evaporation and superheating zones), for Once-Through (the intermediate water-steam separator and the recirculation pump located in the solar field are not used in this operating mode) and Injection mode (feed water is injected in different points along the collector row). The facility is provided with a wide range of instrumentation for full system monitoring (flow rates and fluid temperatures/pressures in the various zones of the solar field, pressure drops in collectors and piping, temperature and thermal gradients in the cross sections of the absorber tubes, etc.) and a data acquisition and process control system which has a database where 5-s process data are recorded 24 hours a day.

Figure 48. View of the DISS plant solar field in operation

Among the capacities associated with this facility are the following:

- Component testing for parabolic-trough collector solar fields with direct steam generation (DSG) in their receiver tubes (receivers, ball joints or flex hoses, water-steam separators, specific instrumentation, etc.).
- Study and development of control schemes for solar fields with DSG.
- Study and optimization of the operating procedures that must be implemented in solar fields with DSG for electricity generation.
- Thermo-hydraulic study of two-phase of water/steam in horizontal tubes with non-homogeneous heat flux.

The HTF Test Loop

The HTF test loop is an ideal facility for evaluating parabolic-trough collector components under real solar energy operating conditions. The facility is appropriately instrumented for qualifying and monitoring of the following components:

- New designs of parabolic-trough collectors (up to 75 m long).
- Parabolic-trough collector mirrors.
- Parabolic-trough collector absorber tubes.

- New designs of ball-joints or flex-hoses for connecting parabolic-trough collectors in the solar fields.
- Solar tracking systems.

The facility consists of a closed thermal-oil circuit connected to three solar collectors of 75-m long connected in parallel. With the oil pump initially installed only one collector could be operated at a time, while the additional 45 kW oil pump installed in 2022 can operate several collectors at a time (see simplified diagram of the facility in Figure 49). The east-west rotating axis of the solar collectors increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The thermal oil used in this facility (Syltherm 800®) has a maximum working temperature of 420 °C and a freezing point of – 40 °C.

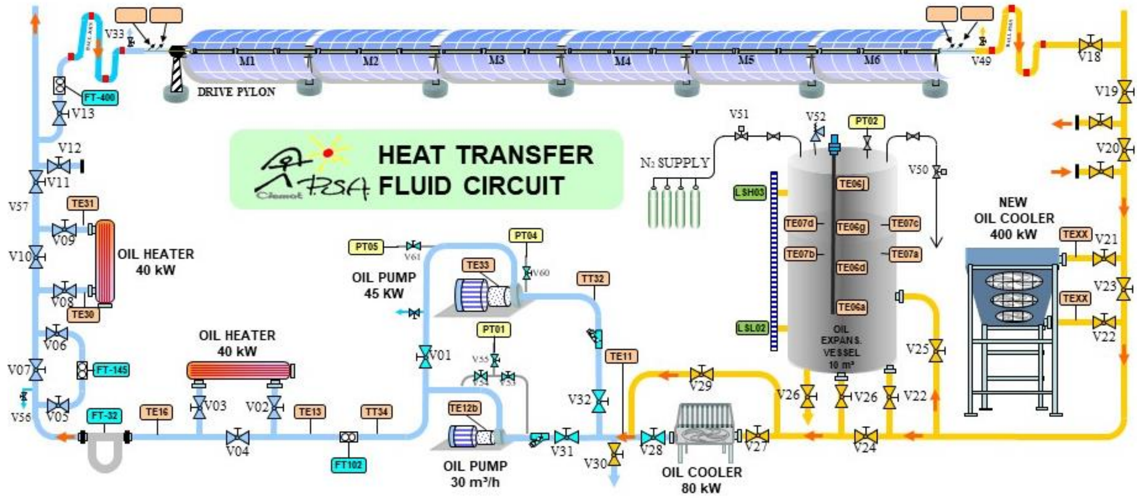


Figure 49. Diagram of the HTF test Loop located at the PSA

The facility's oil circuit, which has a maximum working pressure of 18 bar, is made up of the following elements:

- 10-m³-capacity oil expansion tank, with automatic nitrogen inertization.
- Mechanical-draft oil cooler, with air speed control and 400-kW maximum cooling.
- Centrifugal oil pump, with a flow rate of up to 8.3 litres per second.
- 45 kW Centrifugal oil pump.
- Two 40-kW electric oil heaters.

The first EUROtrough collector prototype developed by a European consortium with the financial aid of the European Commission was installed and evaluated under real working conditions at this facility in 1998. This collector is now used to evaluate and qualify new designs of receiver tubes, reflectors and other components for parabolic-trough collectors.

Main activities at the HTF test loop are related to the study of the optical and thermal performance of complete parabolic-trough collectors (optical efficiency, IAM coefficient, and global efficiency/heat losses) and receiver tubes.

The Parabolic Trough Test Loop (PTTL) facility

This large test facility is implemented in a 420 m x 180 m plot of the PSA and it is composed of two solar fields:

- the North field is designed to install E-W orientation complete parabolic trough collectors with a maximum unit length of 180 m. Up to four complete collectors can be installed in parallel.
- the South field is designed to install complete loops of parabolic trough collectors (PTCs), i.e., several collectors connected in series, with a maximum length of 640 m and oriented North-South. Up to four complete loops can be installed in parallel.

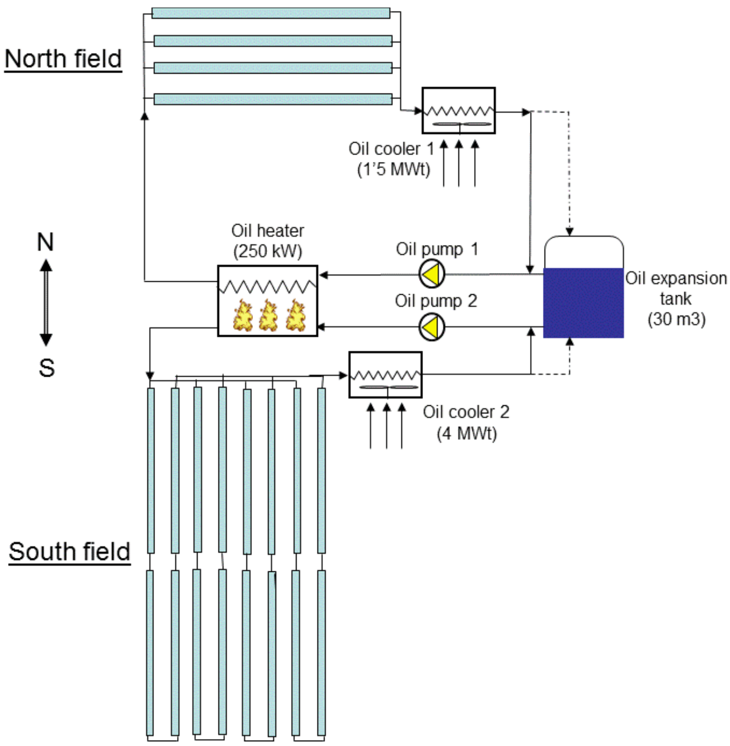


Figure 50. Simplified scheme of the PTTL facility.

Each field is provided with a complete oil circuit installed on a 30 m x 30 m concrete platform between the two fields, and both circuits share: an oil expansion tank with a capacity of 30 m^3, a gas-fired oil heater with a thermal power of 250 kW and a maximum oil temperature of 400 °C, a meteorological station equipped with solar radiation, ambient temperature and wind sensors and the data acquisition system (DAS). Additionally, to these common elements, the oil circuit associated to the North and South fields are composed of:

- North field: one oil pump (75 m^3/h) provided with speed control, one oil cooler refrigerated by air (1.5 MWt) able to cold the oil down to 70 °C when the ambient air temperature is 40 °C, oil piping connecting the circuit to the common elements (i.e., expansion tank and oil heater).
- South field: one oil pump (125 m^3/h) provided with speed control, one oil cooler refrigerated by air (4 MWt), oil piping connecting the circuit to the common elements (i.e., expansion tank and oil heater).

Each oil circuit is also provided with an oil-draining tank big enough to receive all the oil existing in the circuit, a complete set of instrumentation to monitor oil mass flow, pressures and temperatures, as well as control valves to regulate the oil flow to desired values according to the tests.

This outdoor life-size test facility offers the following capacities:

- qualification of complete PTC prototypes assessing their optical peak efficiency, incidence angle modifier and thermal losses.
- evaluation of durability and reliability of PTC mirrors, receiver tubes, ball-joints, flex hoses, sun tracking systems and all the elements installed in complete rows of collectors.
- Evaluation of PTC solar field control algorithms.

PROMETEO: Test facility for checking new components and heat transfer fluids for large-parabolic troughs

This facility is an experimental closed thermal oil loop installed at the Northeast area of the PSA in 2010.

The East-West oriented solar field allows the qualification of all collector components and complete collectors of a length of up to 150 m, i.e., structures, reflectors, receivers from 70 to 90 mm and movable joints. It enables sun tracking covering all solar radiation incidence angles in one day thanks to its orientation. It is equipped with high precision instrumentation and controls for precise, quick and automated measurements. Currently there are two parabolic troughs 100 m-long and with an aperture of 7.5 m, each one installed in the pilot plant.

Figure 51. View of the PROMETEO test facility.

The collector modules can be connected to the balance of plant (BOP) either in parallel or in series configuration using the ad-hoc set valve. The heat transfer fluid used so far in this test facility is silicone oil. A pump circulates the silicone heat transfer fluid (SHTF) with a mass flow similar to that of commercial power plants. Mass flow is measured directly using Vortex and differential pressure flowmeter types. A controlled air cooler unit dissipates the collected thermal energy and ensures a constant HTF temperature (±1 K) at the inlet of the collector. Sensors for measurement of inlet and outlet temperatures are highly precise and may be calibrated on site. A meteorological station delivers accurate radiation and wind data.

TCP-100 2.3-MWth parabolic-trough facility

This test facility was implemented in 2014, and it is composed of the TCP-100 solar field and a storage tank with 115 m^3 of Santotherm-55 thermal oil.

The solar field is composed of six parabolic-trough collectors, model TCP-100, installed in three parallel loops, with two collectors in series within each loop, see

Figure 52. Each collector is composed of eight parabolic trough modules with a total length of 100 m and a parabola width of 5.77 m. The total solar collecting surface of each collector is 545 m^2. The focal distance is 1.71 m, the geometrical intercept factor is ≥0.95, and the peak optical efficiency is 77.5%. Archimede Solar Energy (Italy) delivered the receiver tubes used in this solar field and the working fluid is Syltherm®800.

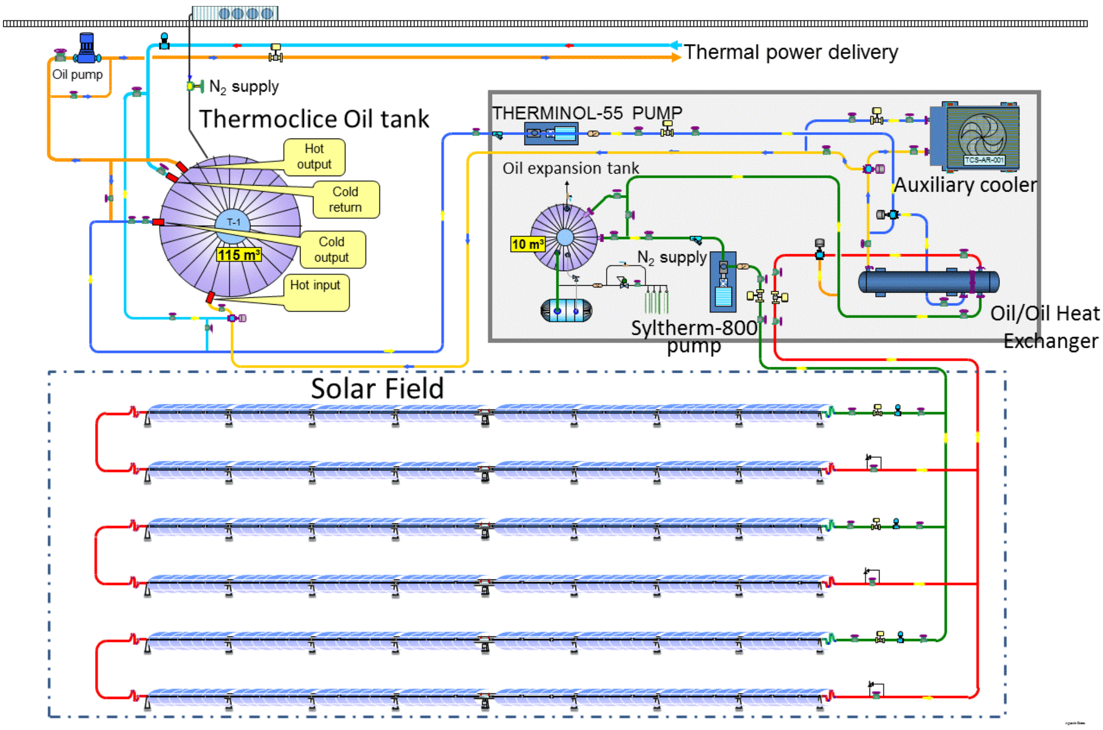


Figure 52. Diagram of the TCP-100 2.3 MWth parabolic-trough facility

The solar field is connected to a 10 m^3 oil expansion tank for a maximum temperature of 400°C. Thermal energy can be transferred from the solar field primary circuit to a thermocline oil storage tank with a total volume of 176 m^3 and 115 m^3 of Santotherm-55 oil with a maximum working temperature of 300 °C.

This test facility is specially designed to perform studies related to control systems for parabolic trough solar fields. This is the reason why two collector loops are provided with the solar tracking system developed by PSA, while the third loop is provided with a commercial solar tracking system with continuous movement. Due to commissioning problems, the facility is not in operation at present.

Innovative Fluids Test Loop (pressurized gases) in parabolic-trough collectors

The purpose of this experimental facility is to study the use of pressurized gases as heat transfer fluid in parabolic-trough collectors, evaluating their behaviour under a diversity of real operating conditions.

The experimental test loop (see Figure 53) is located north of the DISS experimental plant control building, which also houses the equipment necessary for the control and data acquisition of this experimental test loop.

This innovative fluid loop (IFL) can work at pressures and temperatures of up to 100 bar and 515 °C, and consists of the following components:

- Two East-West-oriented EUROtrough parabolic-trough collectors, each 50 m long with a 274.2-m^2 collector surface. The collectors can be connected in series or parallel.
  A 400-kW air-cooler able to dissipate the thermal energy in the fluid delivered by the collectors. It has two 4-kW motorized fans.

Figure 53. View of the IFL experimental facility (with parabolic troughs) using compressed gas as heat transfer fluid.

- A blower driven by a 15-kW motor that supplies the gas flow rate necessary to cool the receiver tubes adequately.
- A data acquisition and control system that allows the temperature, flow rate, pressure, beam solar irradiance and humidity in the system to be completely monitored.
- Automatic control valves that allow precise, safe variation in the collector fluid feed flow rate.
- An auxiliary circuit for filling the main test loop with the gas used as heat transfer fluid.

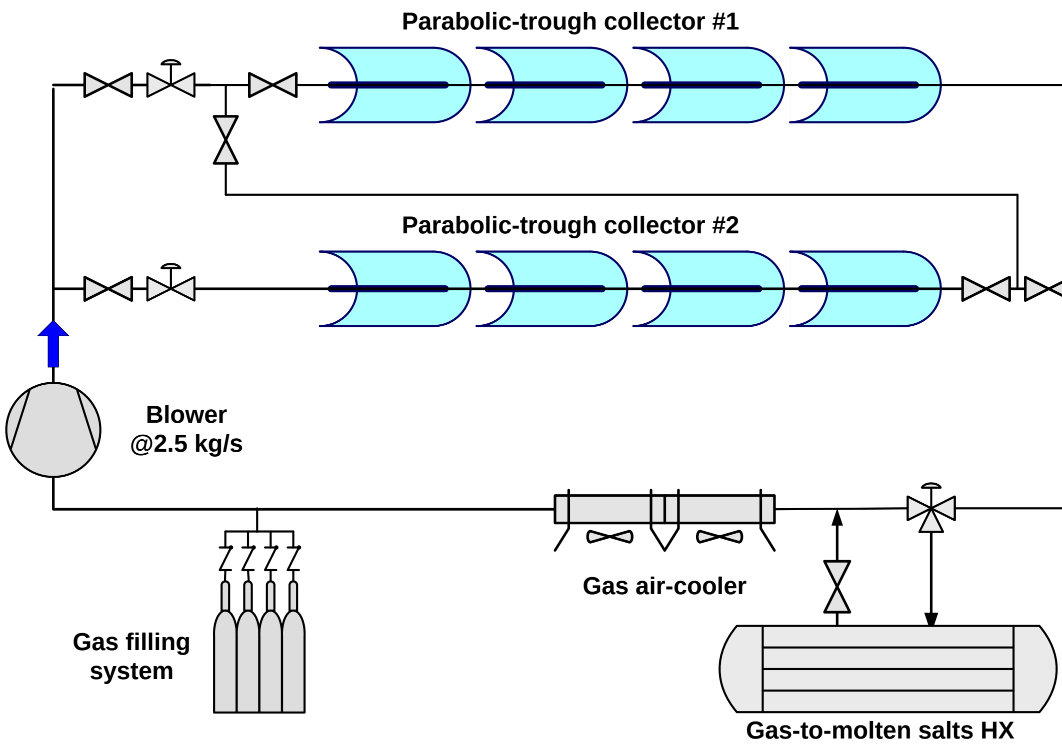


Figure 54. Simplified system diagram of the IFL experimental facility located at the PSA

NEP: The facility for Polygeneration Applications

Polygeneration is an integral process with the purpose of obtaining three or more products from one or more natural resources. In the case of solar energy, it makes use of the thermal energy from a solar field for several simultaneous applications, such as generating electricity, desalting water for drinking water supply and the rest for domestic hot water (DHW).

The purpose of this facility is the preliminary study of the behaviour of a parabolic trough solar field of small concentration ratio, the determination of its feasibility as a heat source in polygeneration schemes, in particular in solar thermal electricity + desalination requiring temperatures around 200°C. The solar collectors installed in this facility are Polytrough 1200 manufactured y NEP Solar. It has a production of 15.8 kW per module (0.55 kW/m^2) under nominal conditions, with a mean collector temperature of 200 °C, and efficiency over 55 % in the range of 120-220 °C (for 1000 W/m^2 of direct normal irradiance).

The field is configured with eight collectors placed in 4 parallel rows, with 2 collectors in series within each row. This configuration supplies 125 kW of thermal energy. The temperature of the thermal oil can be up to 220 °C, so different schemes for making use of the thermal energy for polygeneration can be evaluated.

Currently, the solar field is also being used to generate steam for driving the double-effect absorption heat pump coupled to the PSA MED (Multi Effect Distillation) plant.

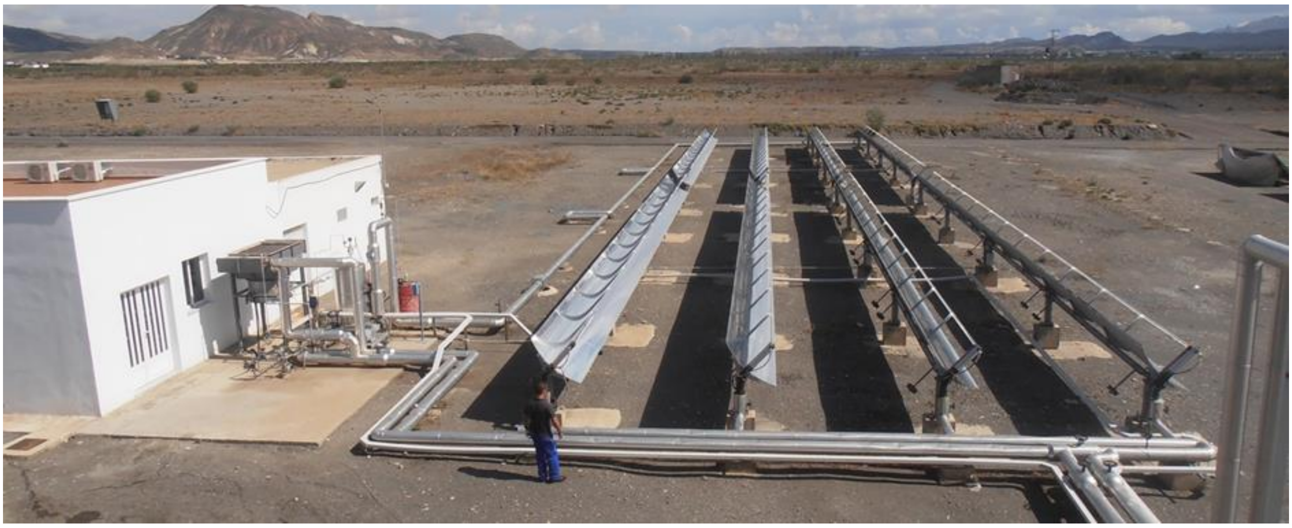


Figure 55. NEP PolyTrough 1,200 solar field.

KONTAS: Rotary test bench for parabolic trough systems

A rotary test bench for parabolic trough collector components, KONTAS, was erected at PSA in 2009. The concept was developed by DLR and within the framework of the Spanish-German agreement between CIEMAT and DLR this test facility is now jointly used by both institutions.

The test bench allows the qualification of all collector components and complete modules of a length of up to 20 m, i.e., structures, reflectors, receivers and flexible joints. It enables for a tracking at any desired angle of incidence of the solar radiation. It is equipped with high precision instrumentation and controls for precise, quick and automated measurements.

This test bench rests on rails directly mounted on top of the foundation. These rails form an inner and an outer ring. The collector itself is mounted on a steel platform with six steel wheels. The rotation of the platform on the rails around the central bearing is performed by motors driving four of these wheels.

The collector module under testing is connected to a heating&cooling unit, which is also situated on the platform. A pump circulates *Syltherm 800®* thermal oil as heat transfer fluid (HTF) with a mass flow similar to that of commercial plants. Mass flow is measured directly using the Coriolis measuring principle avoiding uncertainties of the density. The heating and cooling unit dissipates the energy the HTF collects on the way through the receiver tube of the collector module mounted on the rotating platform and ensures a constant HTF temperature (±1 K) at the inlet of the collector. Sensors for measurement of inlet and outlet temperatures are highly precise and may be calibrated on site. A high precision meteorological station delivers accurate radiation and wind data.

Figure 56. Side view of KONTAS test bench and the heating/cooling unit (right side).

Accelerated full lifecycle tests of rotation and expansion performing assemblies (REPAs) for parabolic troughs systems

The REPA test facility is another test facility jointly implemented at PSA by CIEMAT and DLR. This facility is now used by CIEMAT and DLR in the framework of a joint collaboration.

The test bench is divided into two functional sections, the so-called kinematics unit, to hold and move the pieces REPAs to be tested, and the balance of plant unit for supplying the conditioned heat transfer fluid (see (a) (b)

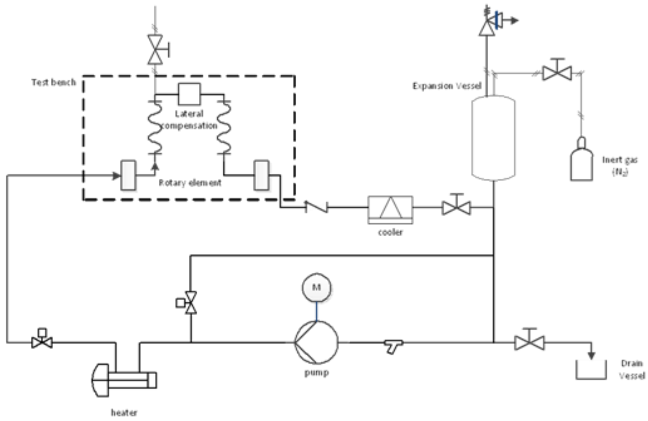
Figure 57.a).

The balance of plant unit is composed of a variable speed HTF pump that circulates the HTF through a pipe provided with an adapted collar-type electrical heaters before passing through the REPA to be tested, placed in the kinematics unit. The return line runs directly to the suction side of the pump closing the circuit. The system is connected to an expansion vessel able to compensate the volume difference caused by the density variation of the working fluid when its temperature changes.

The kinematics unit (see (a) (b)

Figure 57.b) is prepared to accommodate test samples of ball joints and flexible hoses with varying and adjustable geometries, e.g., focal lengths. It is prepared to accomplish both rotational and translational movements with the following characteristics:

- Drive pylon: modified EuroTrough drive pylon structure.
- Rotating angle is 205° and stow position in 25° facing down.
- Up to 45° of lateral motion, representing absorber tube thermal expansion.
- Prepared for dimensions of new PTC designs (focal lengths from 1 m to 2.3 m).
- Measurement of the reaction forces and torques of the assemblies under testing.



(a)

(b)

Figure 57. Schematic diagram of the REPA test loop at PSA (a) and north view of the test facility with two flex-hoses mounted for testing (b).

SMALL-SIZED PTCS PRESSURIZED WATER TEST LOOP - LAVEC

This test facility is specially designed for evaluating and qualifying small line-focus solar collectors using pressurized water as working fluid within the temperature range 100-250 °C, which is very suitable for industrial process heat applications. This test facility fulfils the current standards for solar thermal collectors testing: ASTM E905‑87:2013, SRCC 600 2014‑17:2015 and ISO 9806:2017.

The main technical parameters of the LAVEC facility are the following:

- Heat transfer fluid: pressurized hot water (environmentally friendly fluid).
- Operation gauge pressure: up to 4.2 MPa.
- Operation temperature: up to 250 °C.
- Operation flowrate: from 0.05 to 0.5 $kg \cdot s^{-1}$.
- Expected size of the solar collectors tested: up to 25 m^2 per collector unit.
- Material used for the hydraulic circuit: stainless steel.
- Field length: up to 40 m, in both orientations: East‑West and North‑South.
- Cooling system capacity: up to 150 kWt, depending on the operating conditions.
- Uncertainty of flowrate measurement: better than 1.0 %.
- Uncertainty of inlet/outlet water temperature: ±0.1 °C to 0.525 °C (0 °C to 250 °C).
- Hot water storage tank of 3 m^3.

Figure 58 shows the simplified scheme of LAVEC with a solar collector connected to the system for qualification/evaluation, while Figure 59 is an overall view of the facility. This facility is provided with an innovative equipment to provide the maximum possible accuracy in the assessment of the collector efficiency.

Solar collectors are easily connected to the balance of plant of LAVEC by means of 1” flanges.

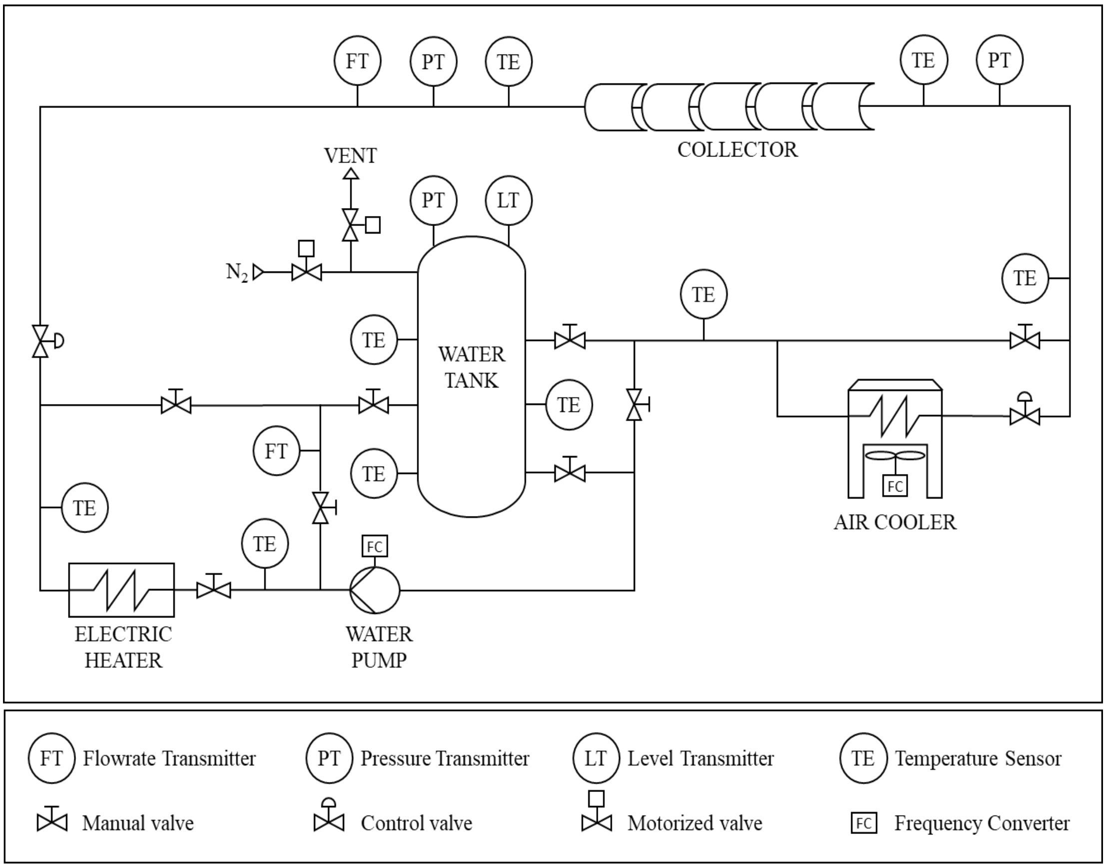


Figure 58. Simplified scheme of the LAVEC facility.

Figure 59. Overall view of LAVEC.

Central Receiver Systems

The PSA has two exceptional facilities for the testing and validation of central system technology, also called power tower technology, components and applications. The SSPS-CRS and CESA-1 facilities enable projects to be undertaken and technologies validated in the hundreds of kilowatts range. They are outdoor facilities specially conditioned for scaling and qualifying systems prior to commercial demonstration.

The 6 MWth CESA-1 Plant

The CESA-1 plant (see Figure 60) was inaugurated in May 1983 to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the CESA-1 plant is a very flexible facility operated for testing subsystems and components such as heliostats, solar receivers, thermal storage, solarized gas turbines, control systems and concentrated high flux solar radiation measurement instrumentation. It is also used for other applications that require high photon concentrations on relatively large surfaces, such as in chemical or high-temperature processes, surface treatment of materials or astrophysics experiments.

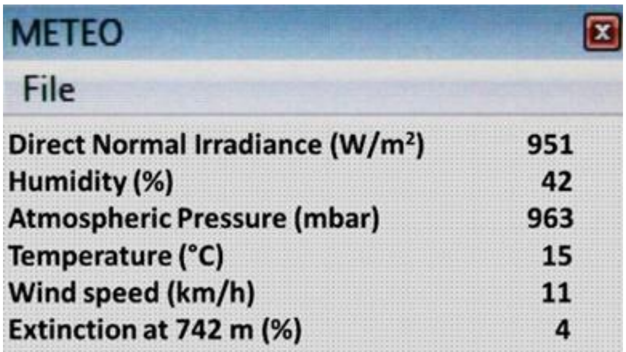
Direct solar radiation is collected by the facility's 330 m x 250 m south-facing field of 300 39.6-m^2 heliostats distributed in 16 rows. The heliostats have a nominal mean reflectance value of 0.91, the solar tracking error on each axis is 1.2 mrad and the reflected beam image quality is 3 mrad. The CESA-1 facility has the most extensive experience in glass-metal heliostats in the world, with first generation units manufactured by SENER and CASA as well as second generation units with reflective facets manufactured by ASINEL and third generation facets and prototypes developed by CIEMAT and SOLUCAR. Despite its over 20 years of age, the heliostat field is in good working condition due to a strategic program of continual mirror-facet replacement and drive mechanism maintenance and replacement.

Figure 60. The CESA-I facility seen from the north.

To the north of the CESA-1 solar field, there are two additional areas used as test platforms for new heliostat prototypes. One located 380 m away from the tower and the other 500 m away from the tower.

The maximum thermal power delivered by the field onto the receiver aperture is 6 MW_{th} at a typical design irradiance of 950 W/m^2, achieving a peak flux of 3.3 MW/m^2. 99 % of the power is focused on a 4-m-diameter circle and 90 % in a 2.8-m circle.

Currently, the measure of solar extinction is available on-line in the control room of the CESA-1 facility at PSA, facilitating the daily operation tasks (Figure 61). Note that this is the first time that it occurs in a solar tower plant. The extinction measurement system has been developed by CIEMAT at PSA and it works taking simultaneous images of the same Lambertian target at very different distances using two identical optical systems with suitable digital cameras, lenses and filters.


METEO

File

Direct Normal Irradiance (W/m²)	951
Humidity (%)	42
Atmospheric Pressure (mbar)	963
Temperature (°C)	15
Wind speed (km/h)	11
Extinction at 742 m (%)	4

Figure 61. On-line measurement of the solar extinction in the control room of CESA-1 facility at PSA.

Currently, there is an airborne particle counter in operation from which measurements are of interest for studies of solar extinction, soiling and evaluation of volumetric receivers.

The SSPS-CRS 2.5 MWth facility

The SSPS-CRS plant was inaugurated as part of the International Energy Agency's SSPS (Small Solar Power Systems) project in September 1981. Originally conceived to demonstrate continuous electricity generation, it initially used a receiver cooled by liquid sodium that also acted as the thermal storage medium. At present, this test facility is mainly devoted to testing small solar receivers in the 200 to 500 kW_{th} capacity range.

Figure 62. Aerial view of the experimental SSPS-CRS facility.

The heliostat field is composed of 91 39.3-m^2 first generation units manufactured by Martin-Marietta. A second field north of it has 20 52-m^2 and 65-m^2 second-generation heliostats manufactured by MBB 7and ASINEL.

The original SSPS-CRS heliostat field was improved several years ago with the conversion of all its heliostats into completely autonomous units powered by photovoltaic energy, with centralized control communicated by radio using a concept developed and patented by PSA researchers (Figure 63). This first autonomous heliostat field, which does not require the use of channels or cabling, was made possible by financial assistance from the Spanish Ministry of Science and Technology's PROFIT program.

The nominal average reflectivity value of the field is currently at 90 %, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m^2, total field capacity is 2.5 MW_{th} and its peak flux is 2.5 MW/m^2. 99 % of the power is collected in a 2.5-m-diameter circumference and 90 % in a 1.8-m circumference. The 43-m-high metal tower has three test platforms. The two first are located at 28 and 26 m and are prepared for testing new receivers for thermochemical applications. The third test platform is at the top of the tower at 43 m and houses an enclosed room with crane and calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers, and solar reactors for hydrogen production. The tower infrastructure is completed with a 4-TN-capacity crane and a 1000-kg-capacity rack elevator.

Figure 63. An autonomous heliostat in the SSPS-CRS field.

The SSPS-CRS tower is equipped with a large quantity of auxiliary devices that allow the execution of a wide range of tests in the field of solar thermal chemistry. All test levels have access to pressurized air (29 dm^3/s, 8 bar), pure nitrogen supplied by cryogenic plant, where liquid N_2 is stored in a liquid tank with a 6 TN capacity. This installation is safe and efficient to operate, and it is extremely versatile to provide all the possible variants. This plant is able to provide N_2 flow rates from 70 kg/hour to 250 kg/hour with autonomy of several days or even weeks. There are also steam generators with capacity of 20 and 60 kg/h of steam, cooling water with a capacity of up to 700 kW, demineralized water (ASTM type 2) from an 8 m^3 buffer tank for use in steam generators or directly in the process, and the data network infrastructure consisting of Ethernet cable and optical fibre.

A hybrid heat flux measurement system to measure the incident solar power that is concentrated by the heliostat field is located at the SSPS-CRS tower. This method comprises two measurement systems, one direct and the other indirect. The direct measurement system consists of several heat flux sensors with a 6.32 mm front-face diameter and a response time in microseconds. These micro sensors are placed on a moving bar, which is mounted in front of the reactor window. The indirect measurement system works optically with a calibrated CCD camera that uses a water-cooled heat flux sensor as a reference for converting grey-scale levels into heat flux values.

At 25 m level, a cantilever with heat shield can be used to position a (optical or IR) camera only a few meters from the aperture.

AORA Solar Tower facility

At the end of 2019, a new tower facility was incorporated to the PSA infrastructures catalogue. The AORA Solar Tower facility is a 35 m tall tower with a pressurized volumetric receiver (porcupine type receiver) installed on it, to heat up air at 15 bar pressure at nominal temperature of 800°C; coupled to a 100 kWe solarized gas turbine from Ansaldo. The 880 m^2 solar field is composed by 55 heliostats of 16 m^2 reflecting surface each of them. Hot air from the turbine exhaust can be used also for cogeneration and/or poli-generation: extra 175 kW_{th} power air is available for driving thermal processes at medium to low temperature (<250°C).

Figure 64. General view of the AORA solar tower facility.

Parabolic DISH Systems

Accelerated ageing test bed and materials durability

This installation consists of 2 DISTAL-II model parabolic dish units with 50 kW total thermal power per unit and two-axis sun tracking system. In the DISTAL-II dishes, the initial Stirling motors have been replaced by different test platforms to put the materials or prototypes at small scale of high concentration receivers and perform accelerated temperature cycling. With fast focusing and defocusing cycles, the probes placed in the concentrator focus stand a large number of thermal cycles in a short time interval, allowing an accelerated ageing of the material. These platforms can be used for a large variety of applications: durability testing of materials, air-cooled volumetric receivers' tests (metal or ceramic), tests of small-size receiver prototypes with or without heat transfer fluid, etc.

The DISTAL-II parabolic dishes (Figure 65) were erected at PSA in 1996 and 1997, using the stretched membrane technology. These parabolic dishes have a diameter of 8.5 m and the thermal energy delivered in the focus is 50 kW_{th}. The focal distance is 4.1 m and the maximum concentration is 16000 suns at the focus. These concentrators can be used for any experiment requiring a focus with the characteristics above mentioned (50 kW_{th} maximum and 16000 suns peak concentration at the focus). The tracking consists in a two-axis azimuth-elevation system.

The test bed for durability and accelerated materials ageing is complemented with the laboratory for the assessment of the durability and characterization of materials under concentrated solar radiation (Materbla) existing at PSA, which is described in the laboratories section of this document (section 30).

Figure 65. View of a parabolic-dish DISTAL- II with the original Stirling engine.

Figure 66. Accelerated aging tests of steel samples at a parabolic-dish DISTAL- II

EURODISH

Under the Spanish-German EUROdish Project, two new dish/Stirling prototypes were designed and erected (Figure 67), discarding the stretched-membrane technology and applying a moulded composite-material system. These parabolic dishes can be used to test new prototypes of Stirling engines, or to perform any other test requiring a focus with 50 kW_{th} maximum and a maximum concentration of 16000 suns at the focus. The tracking system is azimuth-elevation.

Figure 67. Front and back views of the EURODISH.

Solar Furnaces facility

SF-60 Solar Furnace

The SF60 consists, basically, on a 130 m^2 flat heliostat that reflects the solar beam onto a 100 m^2 parabolic concentrator that in turn concentrates the incoming rays on the focus of the parabola, where the tested specimens are placed. A louvered shutter placed between the heliostat and the concentrator regulates the incoming light. Finally, a test table, which movable on three axes, is used to place the specimens in the focus. The heliostat collects solar radiation and redirects it to the concentrator. The heliostat's reflective surface is made up of flat, non-concentrating facets, which reflect the sun's rays horizontally and parallel to the optical axis of the parabolic-dish concentrator, continuously tracking the sun.

The heliostat associated with the SF-60 consists of 130 flat facets, with 1 m^2 reflecting surface each. These facets have been designed, manufactured, assembled and aligned by PSA technicians. Every facet is composed of a 1 m^2 reflecting surface and 3 mm thick Rioglass flat mirror silvered on its back (second surface mirror). Solar Furnace Technicians are also responsible of a new method of fixation of the facet on a frame that minimizes deformation of the reflecting surface. Figure 68 and Figure 69 show the heliostat installed in this solar furnace and a detail of the backside of the facet, respectively.

The parabolic concentrator is the main component of solar furnace. Its function is to concentrate the sunlight reflected by the heliostat, multiplying the radiant energy in the focus. After thirty years in operation, the rectangular facets of the ancient Mc Donnell Douglas concentrator had deteriorated, showing optical defects and large surface undulation that affected its efficiency. That is why we decided to replace them with new ones with lower surface error and higher reflectivity and efficiency, so new facets with hexagonal-shaped mirrors were designed and manufactured at the Solar Furnace.

For the installation of the new facets, the original structure of the Mc Donnell Douglas concentrator was partially used, removing the excess part of the above-mentioned structure, and a new tubular structure was adapted to the remaining part of the original structure and serves to support the assembly. Finally, the facets were attached to the new tubular structure.

Figure 68. HT120 heliostat in tracking.

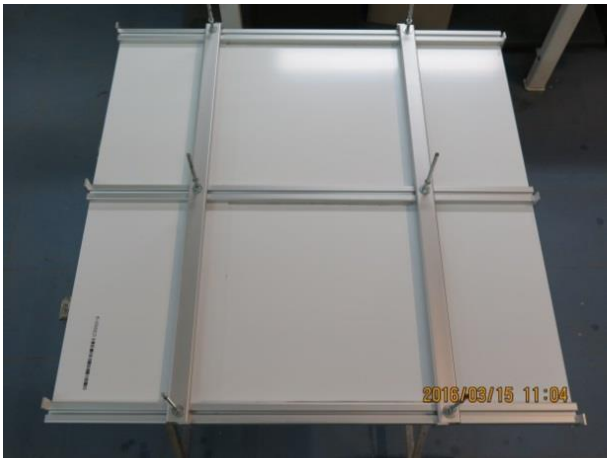


Figure 69. Back side of facet

The new parabolic concentrator, called FAHEX 100 (Figure 70), is made of 463 facets grouped by their radius of curvature in three groups, depending on their distance from the focus. The facets with the smallest radius of curvature are located around the vertex of the parabola, followed by the facets with an intermediate radius of curvature, and finally, the facets with the largest radius of curvature are in the farthest part from the vertex of the concentrator.

The shutter (attenuator), see Figure 71, consists of a set of horizontal louvers, which turn on their axis to control the amount of sunlight incident on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter. The test table is a mobile support for the test pieces or prototypes to be tested that is located under the focus of the concentrator. It moves on three axes (X, Y, Z) perpendicular to each other and positions the test sample with great precision in the focal area.

The combination of all the components described lead to the flux density distribution in the focus that is what characterizes a solar furnace. This distribution usually has a Gaussian geometry and is characterized by a CCD camera hooked up to an image processor and a Lambertian target. The characteristics of the focus with 100% aperture and solar radiation of 1,000 W/m^2 are: peak flux, 670 W/cm^2, total power, 80 kW, and focal diameter, 22 cm.

Figure 70. Interior view of the PSA SF-60 Solar Furnace in operation.

Figure 71. Shutter of the PSA SF-60 Solar Furnace.

SF-40 Solar Furnace

The SF-40 furnace consists mainly of an 8.5-m-diameter parabolic-dish, with a focal distance of 4.5 m (see Figure 72). The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive thin-glass mirrors on the front. The parabola thus formed is held at the back by a ring spatial structure to give it rigidity and keep it vertical. The new SF40 solar furnace reaches a peak concentration of 5,000 suns and has a power of 40 kW, its focus size is 12 cm diameter and rim angle a= 50.3°. Its optical axis is horizontal, and it is of the “on-axis” type that is parabolic concentrator, focus and heliostat are aligned on the optical axis of the parabola.

It consists of a 100 m^2 reflecting surface flat heliostat, a 56.5 m^2 projecting area parabolic concentrator, slats shutter, and test table with three-axis movement.

The focus of the SF40 is arranged on the vertical plane. In order to work on the horizontal plane, the beam rays incident into focus are rotated 90°, using a tilted, cooled mirror placed at the focal area, which turn the beam to the horizontal plane. The facility is completed with a gas system and vacuum chamber -MiniVac 2-, which allows tests in controlled atmosphere and vacuum conditions, so that the specimens are not oxidized during tests.

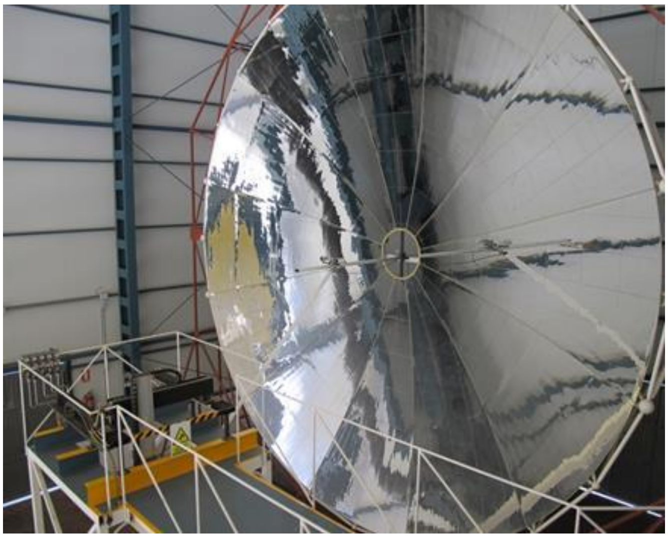


Figure 72. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

SF-5 Solar Furnace

Designed and built at the PSA, this system is in operation since 2012 and is focused on carrying out tests that require high radiant flux, strong gradients, and very high temperatures.

It is called SF5 (Solar Furnace 5), due to its 5-kW power-, reaches concentrations above 7000 suns, its focus diameter is 2.5 cm, and it is mainly devoted to heat treatment of materials at high temperatures, under vacuum and controlled atmosphere conditions, for which a vacuum chamber, called Spherical Chamber, provided with a gas system is used.

It differs substantially from the existing PSA Solar Furnace SF60 and most operating solar furnaces, as it operates in a vertical axis, i.e., parabolic concentrator and heliostat are vertically aligned on the optical axis of the paraboloid, while in most existing solar furnaces, they are horizontally aligned. The main advantage of vertical axis solar furnaces is that the focus is arranged in a horizontal plane, so that the samples may be treated on a horizontal surface, just placing them directly in the focus, without a holder, avoiding problems of loss of material by gravity in those tests in which the treatment requires surface melting of the specimens.

It basically consists of an 8.7 m^2 concentrator mirror, placed upside-down with the reflecting surface facing the floor, on an 18 m high metallic tower; in the centre of the base of the tower there is a 12 m^2 flat heliostat, whose centre of rotation is aligned with the optical axis of the concentrator. At the top of the tower, in the test room, and 2 m below the vertex of the concentrator, there is a test table. Finally, under the test table and at floor level of the test room, a louvered attenuator is placed.

Figure 73. Concentrator of the SF-5 Furnace.

Optical characterization and solar reflector durability analysis facility - OPAC

The PSA optical characterization and solar reflector durability analysis facility, which is the result of a joint collaborative project between CIEMAT and DLR, has the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. This laboratory allows the evaluation of characteristic optical parameters of solar reflectors and their possible deterioration. The following equipment is available in the laboratory of optical characterization of solar reflectors (see Figure 74a):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 15° incidence angle, 660 nm wavelength and different aperture angles (3.5, 7.5, 12.5 and 23 mrad).
- One portable specular reflectometer, Devices and Services model MWR, for measuring specular reflectance at 15° incidence angle, 460, 550, 650 and 720 nm wavelength and at different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- One portable reflectometer, PSE model pFlex 2.1, for measuring specular reflectance at 8° incidence angle, 470, 525 and 625 nm wavelength, and 67 mrad aperture angle.
- One portable reflectometer, Aragon Photonics model Condor, for measuring specular reflectance at 12° incidence angle, 435, 525, 650, 780, 940 and 1050 nm wavelength and 145 mrad aperture angle.
- One portable reflectometer, Konica Minolta model CM-700d, for measuring hemispherical and diffuse reflectance at 8° incidence angle, and 400-700 nm wavelength.

- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model SR^2, designed and patented by DLR).
- Spectral Specular Reflectometer S2R for measuring specular reflectance spectra in the wavelength range 280-2500 nm at variable incidence angles of 8-70° and discrete acceptance angles of 7.4, 12.3, 14.8, 20.2, 35.9 and 107.4 mrad (designed and patented by DLR).
- Two Perkin Elmer Lambda 1050 spectrophotometers, with two 150-mm integrating spheres and specular reflectance accessory with 0 to 68° incidence angles (URA).
- One infrared spectrometer, Perkin Elmer FT-IR.
- Nikon D3 camera and 90 cm Cubalite kit for photos of specular surfaces without parasitic reflections.
- Zeiss Axio microscope model CSM 700 (with magnifications of 5, 10, 20, 50 and 100) for finding the profiles and roughness of highly reflective surfaces.
- Parstat 4000 impedance system to analyse the corrosion of reflector materials.
- General Purpose Optical bench as accessory for the Perkin Elmer Lambda 1050 spectrophotometer with advanced features for mounting optical devices for the development of new measurement instruments.
- Attension Theta 200 Basic tensiometer for static and dynamic contact angle assessment, which is a key parameter to study the performance of the anti-soiling coatings applied to solar reflectors and receiver tubes.

The solar reflector durability analysis laboratory is designed for accelerated ageing tests of these materials with the purpose of predicting in a short time, the behaviour of these materials during their useful lifetime (see Figure 74.b). To do this, the environmental variables producing degradation of solar reflectors when they are exposed to outdoor conditions are applied in a controlled manner, both separately and in combination. The following equipment is available for these accelerated ageing tests:

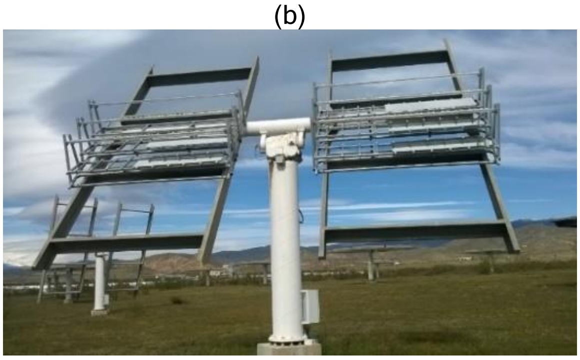
- Two ATLAS SC340MH weathering chambers for temperature (from -40 °C to +120 °C), humidity (from 10 % to 90 %), solar radiation (from 280 to 3,000 nm) and rainfall of 340 L.
- Vötsch VSC450 salt spray chamber with temperatures from 10 °C to 50°C (450 L).
- Erichsen 608/1000 L salt spray chamber with temperatures from 10 °C to 50 °C.
- Two ATLAS UV-Test radiation chambers where UV light (with a peak at 340 nm), condensation and temperature can be applied. One of the chambers also includes rain simulation.
- MKF 720 test chamber, where UV light (with a peak at 340 nm) can be applied in combination with a wide range of temperature and humidity conditions.
- Hönle UVA Cube Ultraviolet radiation chamber.
- SC100 heated water bath, to perform the Machu test, according to the Qualitest guideline.
- Vöstch VCC3 0034 weathering chamber to test the material resistance against corrosive gasses (335 L, see Figure 74.b).
- Ineltec CKEST 300 test chamber for humidity and condensation testing with temperatures up to 70°C (300 L).
- Memmert HCP108 weathering chamber to apply humidity (20-95 %) and temperature (2,090 °C) with humidity and 20-160 °C without humidity).
- Two Nabertherm LT 24/12 and LT 40/12 Muffle Furnaces.

- Control Técnica/ITS GmbH sandstorm chamber with wind speeds up to 30 m/s and dust concentrations up to 2.5 g/m³.
- Erichsen 494 cleaning abrasion device to test the degradation due to the cleaning brushes, with several cleaning accessories.
- Taber 5750 linear abraser to check the materials resistance against the abrasion.
- Lumakin A-29 cross-cut tester to analyse the possible detachment of the paint layers.
- Soiling Pipe for simple sand erosion experiments based on DIN 52348. Erodent material hitting the specimen after around 160 cm of free fall under adjustable impact angles (designed by DLR).
- Artificial soiling chamber, equipped with the aerosol generator SAG410/L from TOPAS GmbH and an ultrasonic nebulizer to reach a realistic soiling picture on reflector samples (designed by DLR).
- Several devices for thermal cycles specially designed at the PSA.

(a)

(b)

(c)



(d)

Figure 74. (a) Optical characterization lab, (b) durability analysis lab, (c) outdoor test bench and (d) outdoor accelerated aging test bench at OPAC facilities.

Along with these labs, there are a series of outdoor test benches for exposing materials to outdoor weather conditions and comparing their degradation with those found in the accelerated ageing tests, to study the effectiveness of special coatings, to optimize the cleaning strategy and to analyse the soiling rate. In addition, two heliostat test benches were recently installed, one to test the influence of blocking on the coatings lifetime and another one to accelerate the reflectors degradation due to UV radiation under outdoor weather conditions. Finally, the laboratory is equipped with accessories necessary for their proper use, such as precision scales, thermo-magnetic stirrer, drier, ultrasonic bath for sample cleaning, tools for reflector samples preparation (cutting and polishing), safety cabinets, instrumentation for measuring pH, conductivity, oxygen, etc.

Thermal Storage Systems

MOSA: Molten Salt Test Loop for Thermal Energy Systems

This facility is composed by an outdoor test loop with about 40 t of molten solar salt mixture and an indoor test bench filled with about 115 kg of salt.

The outdoor loop of MOSA is the largest facility worldwide similar to a commercial thermal energy storage system with a two-tank configuration but on a reduced scale. Hence, this facility allows performing different kinds of tests in relevant environment and extrapolated scale. Some applications of this facility are:

- Testing of different circuit component (pumps, flowmeters, etc.) to be used in molten salts conditions.
- Optimization of operation procedures for two-tank storage system configuration.
- Optimization of operation procedures in risky situations for a two-tank storage system configuration and design of recovery procedures.
- Validation of models and simulation approaches for molten salt based thermal systems.
- Characterization of heat exchangers for molten salt/oil.
- Characterization of thermocline tanks.

For more information see M.M. Rodríguez-García, M. Herrador Moreno, E. Zarza Moya, 2014, Lessons learnt during the design, construction and start-up phases of a molten salt testing facility, Applied Thermal Engineering, 62 - 2, 520-528, ISSN 1359-4311.

The indoor test bench called BES-II, is especially designed for testing valves, pressure transmitters and other small components of molten salt circuits under quasi real working conditions up to 600°C and 40 bar. Components with nominal diameters from 2" up to 6" can be evaluated in this test bench.

Figure 75. Molten Salt (MOSA) outdoor test loop.

Figure 76. MOSA indoor test bench (BES-II).

For more information see M.M. Rodríguez-García, E. Rojas, M. Pérez, 2016, Procedures for testing valves and pressure transducers with molten salt, Applied Thermal Energy, 101, 139-146.

ALTAYR: Atmospheric Air Packed Bed Test Bench

This facility is an insulated storage tank of around 0.1 m^3 where different packed bed configurations and materials can be tested using atmospheric air as heat transfer fluid. Provided with a maximum electric power of 15 kW, a charge process with air up to 850°C is possible. Thermocouples along its length and at different radial positions give an accurate map of the packed-bed temperature.

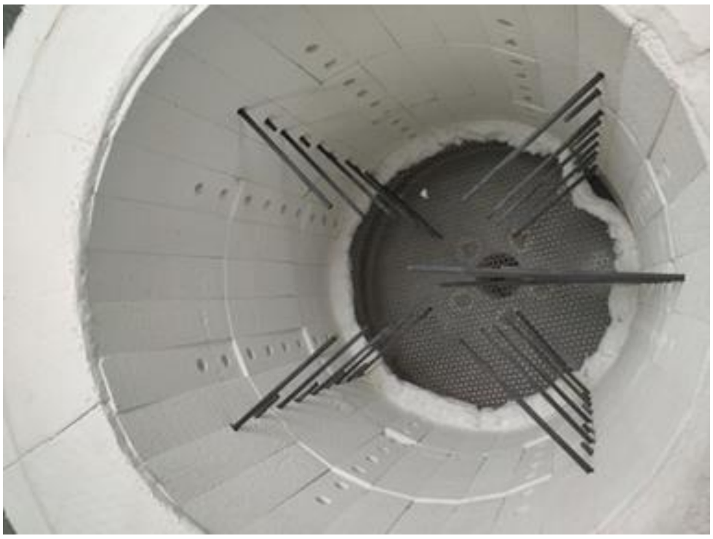


Figure 77. Picture taken from the top of the tank, showing its internal room and thermocouples at different lengths and radial positions.

Figure 78. Researcher adjusting some items from the upper top of the tank.

Experimental Solar Desalination Installations

Multi-Effect Distillation Facilities

Solar Multi-Effect Distillation Facility

This facility is composed of the following subsystems:

- A 14-stage multi-effect distillation (MED) plant
- A field of stationary large-size flat plate solar collectors
- A water-based solar thermal storage system
- A double effect (LiBr-H_2O) absorption heat pump
- A fire-tube gas boiler

The multi-effect distillation unit is made up of 14 stages or effects, arranged vertically with direct seawater supply to the first effect (forward feed configuration). At a nominal 8 m^3/h feedwater flow rate, the distillate production is 3 m^3/h, and the thermal consumption of the plant is 190 kW_{th}, with a performance ratio (number of kg of distillate produced per 2326 kJ of thermal energy consumed) over 9. The saline concentration of the distillate is around 5 ppm. The nominal temperature gradient between the first cell and the last one is 40°C with a maximum operating temperature of 70°C in the first cell. The system heat transfer fluid is water, which is heated as it flows through the solar collectors and energy collected is then transferred to the storage system. The hot water from this storage system provides the MED plant with the thermal energy required for its operation.

The solar field (AQUASOL-II) is composed of 60 stationary flat plate solar collectors (Wagner LBM 10HTF) with a total aperture area of 606 m^2 and is connected with a thermal storage system (40 m^3) through a heat exchanger.

(b)

(c)

(a)

Figure 79. The PSA SOL-14 MED Plant (a) double-effect LiBr-H_2O absorption heat pump (b) and 606-m^2 flat plate solar collector field with tracking mirrors(c).

The double effect (LiBr-H_2O) absorption heat pump is connected to the last effect of the MED plant. The low-pressure saturated steam (35°C, 56 mbar abs) generated in this last effect supplies the heat pump evaporator with the thermal energy required at low temperature, which would otherwise be discharged to the environment, cutting in half the thermal energy consumption required by a conventional multi-effect distillation process. The fossil backup system is a propane water-tube boiler that ensures the heat pump operating conditions (saturated steam at 180°C, 10 bar abs), as well as operating the MED plant in the absence of solar radiation.

Test-Bed for Solar Thermal Desalination Applications

The purpose of this facility is the study of the efficiency of large-aperture static solar collectors and its behaviour in the coupling with thermal desalination systems 60-90 °C temperature levels.

The collector model installed is an LBM 10HTF with an aperture area of 10.1 m^2, manufactured by Wagner & Co. The static solar field is composed of 60 collectors with a total aperture area of 606 m^2 and a total thermal power output of 323 kW_{th} under nominal conditions (efficiency of 59 % for 900 W/m^2 global irradiance and 75 °C as average collector temperature).

It consists of 4 loops with 14 large-aperture flat plate collectors each (two rows connected in series per loop with 7 collectors in parallel per row), and one additional smaller loop with 4 collectors connected in parallel, all of them titled 35° south orientation. The solar field has rows of moving flat mirrors installed at the south of every row of collectors, they can track the Sun and reflect it, enhancing the radiation on each collector. This way, the effective aperture of the solar field can be augmented by 40 % using the same collector surface area. The five loops of collectors are connected with a thermal storage system through a heat exchanger. The thermal storage system consists of two connected water tanks for a total storage capacity of 40 m^3. This volume allows sufficient operational autonomy for the fossil backup system to reach nominal operating conditions in the desalination plant. The facility has an air cooler that allows the entire energy dissipation from the solar field, which is useful for efficiency tests at different temperature levels.

Figure 80. Aerial view of the 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II).

The flexibility of the solar field allows the operation of each loop independently, through their own valves and pumping system. Each loop is connected to an individual heat exchanger that offers the possibility of coupling it with any low-temperature thermal energy consuming device for testing purposes. Two of these loops are currently connected to heat distribution systems to supply thermal energy to membrane distillation test-beds and brine concentration pilot plants.

CSP+D test facilities

CSP+D Test Bed: Integration of MED Thermal Desalination & Solar Thermal Power Plants

This facility is devoted to the research of the coupling between concentrating solar power (CSP) plants and Desalination (CSP+D). The testing facility is composed of two steam generators (250 kW and 500 kW) fed by thermal oil coming from a parabolic trough solar field able to deliver thermal oil with temperatures up to 400 °C and an auxiliary electrical power system that raises the temperature if required. The steam generators can produce steam at different pressures, which allow recreating any of the typical intermediate extractions or the exhausted steam available at a turbine of a thermal power plant. The low-pressure steam is obtained by making the steam from the generators to flow through two different pipe sections (12-inch diameter) equipped with control valves, which allows achieving saturated steam at two different levels: 0.074 bar/42 °C (nominal flow rate of 119 kg/h, maximum flow rate of 360 kg/h) and at 0.16 bar/58 °C (nominal flow rate of 195 kg/h, maximum flow rate of 360 kg/h).

(a) (b)

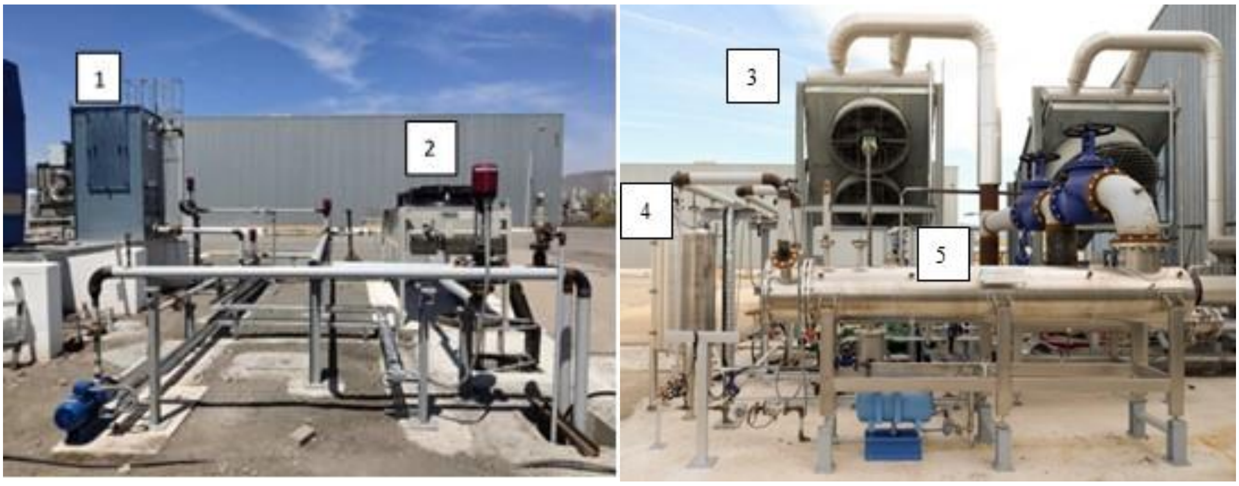
Figure 81. View of the outside of the CSP+D test bed building with the air coolers (a) and partial view of the interior of the CSP+D test bench (b).

Both, the high- and low-pressure steam can be used as motive and entrained vapour, respectively, in a train of four steam ejectors coupled to the PSA MED plant, simulating the behaviour of a MED plant working with thermal vapour compression (TVC-MED). The steam ejectors can work in a wide range of pressure conditions for the motive steam (40 – 6 bar; 4 – 2 bar), which also makes this test bed useful for the characterization of such kind of devices. The low-pressure steam can also be condensed through two conventional air condensers without passing by the steam ejectors, with the aim of allowing research in CSP cooling topics. The flexibility of the test facility also allows the on-site evaluation of innovative dry coolers prototypes for their comparison with respect to the conventional air condensers currently available at the market.

Hybrid-cooling pilot plant

This test facility is a completed equipped pilot plant to evaluate innovative cooling systems for CSP plants. The innovative cooling system is a hybrid cooler composed of a wet cooling tower and a dry cooling tower (Air Cooled Heat Exchanger). The hydraulic circuit of the test bench has been designed to enable the testing of the wet and dry cooling separately and the series and parallel configurations. The testing facility also can compare a hybrid cooling system with a conventional air-cooled condenser.

The hybrid cooling test facility consists of three circuits: cooling circuit, exchange circuit and heating circuit. In the cooling circuit, cooling water circulating inside the tube bundle of a surface condenser is cooled down through a hybrid cooler composed of an Air Cooled Heat Exchanger (200 kW_{th}) and a Wet Cooling tower (200 kW_{th}), functional prototypes that have been built by the French company Hamon D'Hondt. In the exchange circuit, an 80 kW_{th} steam generator produces saturated steam (in the range of 120-300 kg/h) at different temperatures (42-60°C), which is then condensed in the surface condenser while releasing the condensation heat to the cooling water that is heated. The condensate from the surface condenser goes to a tank that supplies the water to the steam generator by a pump when needed. In the heating circuit, the AQUASOL-II large-aperture flat plate solar collector field provides the hot water to drive the steam generator. The testing facility can also compare the hybrid cooling system with a conventional Air-Cooled Condenser (335 kW_{th}). For that, a bypass has been installed in the exchange circuit so that the steam generator can provide the steam either to the surface condenser connected to the hybrid cooler or to the Air-Cooled Condenser.



(a) (b)

Figure 82. General view of the hybrid-cooling test bed: (a) Cooling circuit: wet cooling tower (1) and air-cooled heat exchanger (2). (b) Exchange circuit: air-cooled condenser (3), condensate tank (4) and surface condenser (5).

Membrane Desalination Test Facilities

The installation is designed for evaluating solar thermal desalination applications. There are two solar fields of flat-plate collectors available: one of 20 m^2 with two parallel rows of five collectors in series (Solaris CP1 Nova, by Solaris, Spain), and another one of 40 m^2 with four large-aperture collectors in parallel (LBM 10HTF, by Wagner Solar, Spain). Both fields are connected to water storages of 1500 litres acting as heat buffers for thermal regulation and storage; they also have a distribution system which enables simultaneous connection of several units. The test-beds allow for a stationary heat supply using the thermal heat storage or for direct supply of solar energy without buffering. The installation is fully automated and monitored (temperatures and flows) and allows for heat flow regulation. The maximum thermal power is 7 kW$_{th}$ in one case and 14 kW$_{th}$ in the other, and hot water can be supplied with temperature up to about 90°C.

The installation has a separate water circuit that can be used for cooling (about 3.5 kW$_{th}$) in the desalination units and as a device for supplying simulated seawater, with the possibility of working in an open or closed loop. In the latter case, both the distillate and brine flows are collected and mixed to be fed again into the desalination units after passing through a heat dissipation system. The installation currently operates with Membrane Distillation modules and has a wide range of different commercial and pre-commercial units from different commercial manufacturers. The list of MD modules that have been evaluated or are under evaluation is:

Plate and frame airgap (AG) MD commercial modules from Scarab (total membrane area 2.8 m^2).

Two plate and frame permeate-gap (PG) MD prototypes from Keppel Seghers (both with total membrane area 9 m^2), a compact one (M33) and another which is split in three separate modules connected in series for higher energy recovery (PT5).

Spiral-wound PGMD commercial modules Oryx 150 from Solar Spring (10 m^2).

Two spiral-wound AGMD modules from Aquastill with membrane areas of 7 m^2 and 24 m^2 each.

WTS-40A and WTS-40B units from Aquaver, based on multi-effect vacuum membrane distillation technology using modules fabricated by Memsys (5.7 m^2 and 6.4 m^2 total membrane area respectively).

Three spiral-wound modules from Aquastill operating in vacuum-enhanced air-gap configuration with membrane areas of 7.2, 24 and 26 m^2 respectively.

(a)

(b)

Figure 83. Internal (a) and external (b) views of the Membrane Distillation experimental test bed within the PSA low-temperature solar thermal desalination facility.

Pilot Plant for Studying Combinations of Forward Osmosis and Reverse Osmosis

The plant has three different units that can be coupled in different ways between them: (i) forward osmosis; (ii) reverse osmosis; (iii) microfiltration. The forward osmosis (FO) unit uses 12 hollow fibre modules (Aquaporin HFF02) with 0.2 mm fiber and 2.3 m^2 total membrane area each one, operating in counter-current flow, inside-out, laid out in a flexible rack that allows combining them in series or parallel configuration. The nominal flow rate is 3.6 m^3/h. The reverse osmosis (RO) unit has four vessels that can be connected in series or parallel, each of which hosting four membranes. The nominal flow rate is 3 m^3/h and the pumping system can work at different pressures up to a maximum of 80 bar. The unit is designed so that SWRO, BWRO or NF membranes can be used. Finally, there is an MF unit with 3 m^3/h nominal flow rate. The installation is completely monitored with pressure sensors, conductivity and flowmeters, and it is designed in a flexible way regarding the interconnection of the units so that FO can be used as a pre-treatment for RO, or NF can be used in combination with FO, and even the FO can be used in PRO mode using the pumping system of the RO unit.

Closed-loop seawater feed system for desalination testing.

The system is composed of three storage tanks connected in series containing a total volume of 300 m^3 of real seawater (Figure 85). The containers are connected to a hydraulic circuit that can supply feed water to the different desalination pilot plants at the required flow rate of each. The circuit also returns the brine and the distilled water back to the containers, so that the total mass and the salinity are conserved. A heat dissipation circuit using a compression chiller maintains the temperature constant in the containers.

Figure 84. Test bed for FO-RO combination research.

Figure 85. Containers filled with real seawater for desalination tests in closed loop.

Experimental Solar Decontamination and Disinfection Installations

The main facilities related with solar water purification are listed and described below:

- Solar CPC (compound parabolic collector) pilot plants.
- Solar simulators.
- UVC-pilot plant.
- Solar Waterfall reactor.
- UV-LED lab system.
- Ozonation pilot plant.
- Solar CPC with direct injection of ozone.
- Nanofiltration pilot plant.
- Pilot plant for photocatalytic production of hydrogen based on solar energy.
- Wet Air oxidation pilot plant.
- Electro-oxidation pilot plant
- Solar UVA monitoring equipment
- Pilot plants for biological treatment.
- Membrane Distillation (MD)/Crystallizer pilot plant.
- Experimental culture camera.

Solar CPC pilot plants

Since 1994, several CPC pilot plants have been installed at PSA facilities (Figure 86). Basically, the solar pilot plants are built by modules which can be connected in series. Each module consists of a number of photo-reactors placed on the focus of an anodized aluminium mirror with Compound Parabolic Collector (CPC) shape to optimize solar photons collection in the photo-reactor tube. The modules are placed on a platform titled 37° horizontally to maximize the global solar collection of photons through the year. In addition, the pilot plants are equipped with added systems for different purposes, such as: sedimentation tanks (for catalyst recovery), heating and cooling systems for temperature control during the experiments, coupling with other treatment technologies like bio-treatment, ozonation, etc. A summarize of the already installed solar CPC reactors is shown in Table 1.

As mentioned in Table 1, CADOX photo-reactor is completely monitored (pH, T, ORP, O_2, flow rate, H_2O_2) and controlled (pH, T, flow rate). Besides, and connected to this photo-reactor, there is a biological water treatment system consisting of three tanks: a 165 L conical tank for wastewater conditioning, a 100 L conical recirculation tank and a 170 L flat-bottom fixed-bed aerobic biological reactor. The fixed-bed reactor is filled with Pall®Ring polypropylene that takes up 90-95 L and can be colonized by active sludge from a MWWTP.

A 2 m^2 CPC collector (Figure 87) with 10 borosilicate glass tubes (50 mm diameter), illuminated volume of 22 L and a total volume of 75 L is connected to four electrochemical cells for experimental research on electro-photo-Fenton processes for decontamination and disinfection of water.

In 2016, a new pilot plant with two modules of 2 m^2-collectors with different mirror shapes (CPC and U mirror type) has been installed at PSA (Figure 88). It is composed by a feeding polypropylene tank of 192 L of total volume and a preparation tank of 92.5 L, connected by gravity to the CPC and U type photo-reactors. The last presents 1.98 m^2 of irradiated surface with a recommended operating volume of 53 L. The whole pilot plant is equipped by a UVA solar sensor and automatically controlled. In addition, the pilot plant is equipped with a solar water-heating panel that allows increasing water temperature prior to filling the photo-reactors.

(a)

(b)

Figure 86. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II.

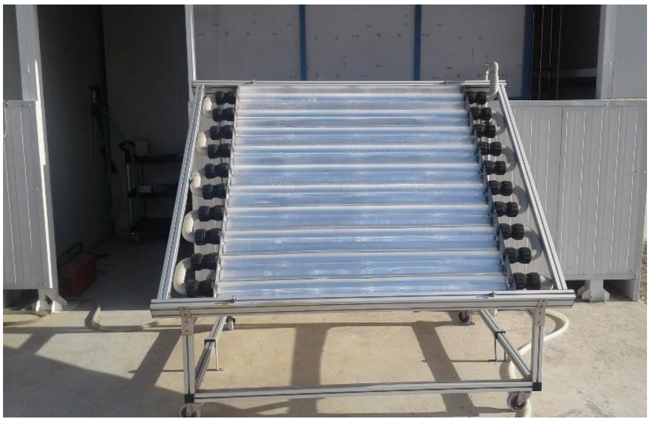


Figure 87. View of 2 m^2-CPC coupled to Electro-Fenton pilot plant (ELECTROX).

Figure 88. View of new CPC and U-type photoreactors (NOVA 75 V 1.0).

Year	CPC (m^2)	Total/illuminated volume (L)	Flow or static	Tube diameter (mm)	Added systems/Characteristics
1994	3x3	250/108	Flow	50	-
2002	15	300	Flow	32	-
2004 (CADOX)	4	75/40	Flow	50	- 50L ozonation system - Biological water treatment system - Monitoring (pH, T, ORP, O_2, flow rate, H_2O_2, O_3), control (pH, T, flow rate)
2007 (SOLEX)	3.08(x2)	40/22	Flow	32	- Twin prototypes - Plexiglass screen - Monitoring dissolved O_2 and temperature - Specially developed for photo-Fenton applications
2008 (FIT)	4.5	60/45	Flow	50	- Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), flow rate). - 100 L sedimentation tank for catalyst separation
2010 (FIT-2)	4.5	60/45	Flow	50	- Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), O_2, flow rate) - Sedimentation tank
2011 (HIDRO-CPC)	2.1	25/14.24	Flow	32	- Coupled with H_2 generation pilot plant
2011 (CPC25)	1	25/11.25	Flow	50	-
2013 (ELECTROX)	2	40/25	Flow	50	- Coupled with electro-photo-Fenton plant
2013 (NOVO75)	2	100/75	Flow	75	- Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate)
2013 (CPC25)	1	25/11.25	Flow or static	50	Variable volume, versatile for different volume of water
2013 (SODIS-CPC)	0.58(x2)	25/25	static	200	Low cost, no recirculation system
2016 (NOVO 75 V1.0)	2.03 (x2)	34 or 53	Flow or static	75	- Two modules of collectors: CPC versus U-mirror type alternatively used - Tubes installed in vertical position - Air injection in tubes - Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate) - Automatic control system for filling the system accordingly to incident energy - Solar panel for water heating

Table 1. Summarize of CPC pilot plants at PSA facilities.

Solar simulators

Along with these pilot-plant facilities, there are two solar simulators provided with xenon lamps for small-scale water decontamination and disinfection experiments. In both systems, the radiation intensity can be modified and monitored. One of the solar simulators XLS+, contains a UV filter (Suprax) with a wavelength limitation of 290 nm, simulating external solar radiation. Temperature can also be modified and controlled in both systems by a cooling system (SUNCOOL).

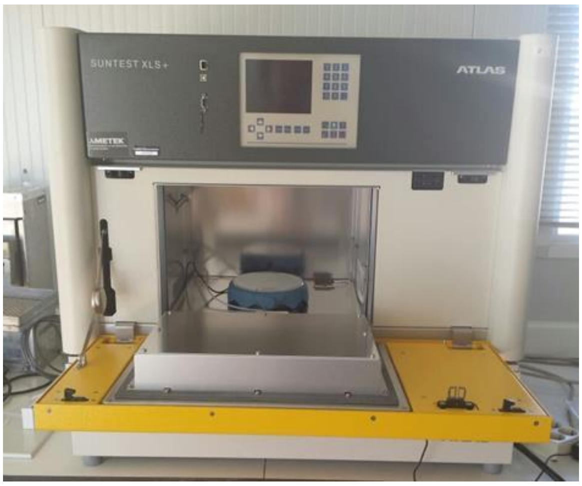


Figure 89. Solar simulator SUNTEST XLS+.

UVC pilot plant

Ultraviolet (UV) pilot plant was designed to treat and disinfect water for research and comparison with the solar technologies. This plant consists of three UV-C lamps (max. flow rate 25 $m^3 \cdot h^{-1}$, 254 nm peak wavelength, 400 $J \cdot m^{-2}$ max. power) connected in series, with the flexible configurations for single lamp, two or three lamps in recirculating batch mode or continuous flow mode. Lamps power and flow rate can be regulated according to the needs of the water. Furthermore, the plant is equipped with a dosage system of reactants (acid, base, and hydrogen peroxide). The total volume per batch is 200 - 250 L, with illuminated volume and area of 6.21 L and 0.338 m^2 per lamp module, respectively. The system is equipped with pH and dissolved oxygen sensors in-line and connected to a PROMINENT controller for automatic data acquisition of both parameters (Figure 90. a).

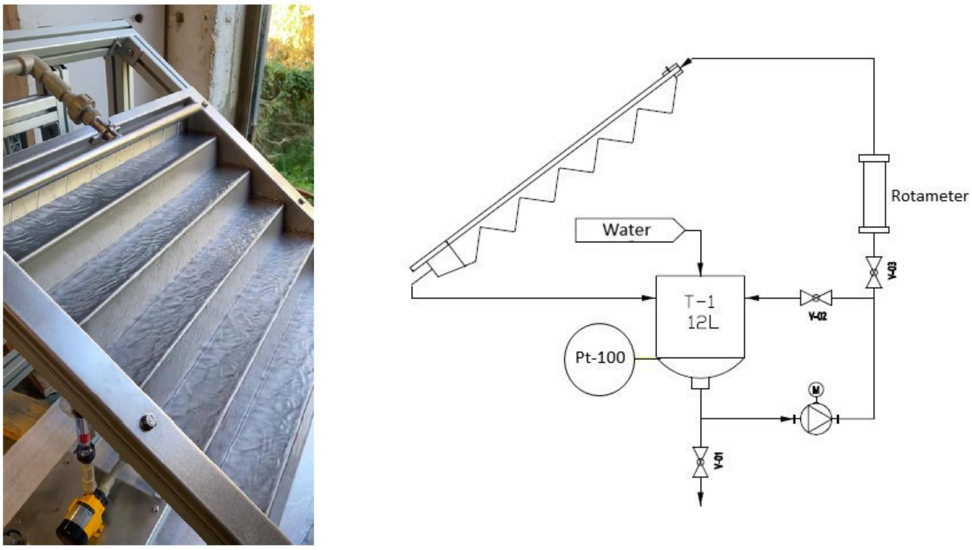
(a) (b)

Figure 90. (a) UVC pilot plant installed at PSA facilities and (b) recent improvements.

The UVC pilot plant was improved (Figure 90.b) not so long ago. A new UVC module with capacity for 3 UVC lamps (model UV Lamp Dulcodes 3 x 230 LP; Max. flow rate 86 $m^3 \cdot h^{-1}$; Lamp power 3 x 260 W; Connected load 825 W; Radiation chamber length 1185 mm) was installed. The new module was connected to the impulsion system (pump) and recirculation circuit (pipes and tank) of the existing plant. There is also a new control panel for monitoring and values registration of the new 3 lamps with six radiation sensors inserted in the frame (Transmittance sensor UVX-SE sensor, Spectral sensor ranges UVC 200 – 280 nm).

Solar Waterfall reactor

The solar waterfall reactor (Figure 91) is based on a waterfall AISI 316L stainless steel structure with polypropylene pipes. Water is distributed from a tank (12 L) to the open waterfall structure by a centrifugal pump (Panworld NH10PX-T) where it will have contact with natural sunlight and a catalyst supported in 5 L-shaped supports with an irradiated surface of 0.42 m^2 (steps, stainless steel AISI-316L 0.8 mm thick). A tubular diffuser has been installed at the top of the reactor for uniform water distribution. A water rotameter (50-500 L/h) and a PT-100 temperature probe are also included. The optimized total and illuminated water volumes are 5 and 1.6 L, respectively.



(a) (b)

Figure 91. Solar waterfall reactor photography (a) and scheme (b).

UV-LED lab system

The UV-LED system at lab scale (LED275-0.01/300-0.03/365-1/450-1cb, provided by APRIA Systems S.L.) consists of the following parts (Figure 92):

- A collimation system. It includes 4 Lamps, concretely, 1 UV-C (λmax = 275 nm), 1 UV-B (λmax = 300 nm), 1 UV-A (λmax = 370 nm) and 1 VIS (λmax = 300 nm) LEDs. Each type of light has an independent control system (on/off and adjustable total radiated power). The system allows simultaneously working with 1, 2, 3 or 4 types of LEDs in different reactors.
- Collimation tubes. 2 collimator tubes (Ølens = 5.08 cm) + 1 collimator lens (λ = 250 - 350 nm, Ø = 5.08 cm, focal length = 6.00 cm); and 2 collimator tubes (Ølens = 5.08 cm) + 1 collimator lens (λ = 350 - 700 nm, Ø = 5.08 cm, focal length = 3.20 cm).
- External shell for the system protection and manipulation including: 4 holes for placing Petri dishes (Ø= 5 cm, V ≈ 35 mL, unsterilized), rings for regulating the distance from the lamp to the reaction device (0 to 3 cm), a console with a control panel for regulation and monitoring the power consumed by the LEDs. LEDs´ temperature is monitored through four PT-100 probes.

Figure 92. UV-LED lab system available at PSA facilities.

Ozonation pilot plant

The ozonation pilot plant is equipped with an oxygen generator (Anseros SEP100), ozone generator (corona-discharge, Anseros COM-AD02), two non-dispersive UV analysers (BMT 964) to measure inlet and outlet ozone concentration in gas phase, a flowmeter for inlet air regulation, reagents dosing system and pH automatic control. Moreover, the pilot plant is equipped with a pH sensor inserted in the recirculation line. In 2016, new instrumentation was added: (i) equipment for humidity elimination in the ozone gas outlet; (ii) Thermo-catalytic residual ozone destructor; and (iii) a dissolved ozone sensor.

In 2020, the ozonation pilot plant was improved with the main objective of increasing the gas-liquid mass transfer of the system. It can be operated in different modes: (i) Bubble column (from 20 to 580 L total volume) (Figure 93.a); (ii) nano-bubble with HP pump (EBARA MVP 9-550/10, 5.5 kW) (from 50 to 110 L in batch mode operation) (Figure 93.b and c); (iii) HidroV mode with a venturi for the generation of micro-bubbles of ozone to be injected in the pressurized tank (110 L) (pump EBARA CDXM/A 90/10, 1.2 kW); (iv) HidroVT with a venturi for micro-bubbles injection into an intermediate tank of 2 L working in recirculation flow with the 110 L pressurized tank (pump EBARA CDXM/A 90/10, 1.2 kW) (Figure 93.d). This ozonation system is prepared to work in batch mode allowing its combination with other technologies such as, CPC photo-reactors, photocatalyst and the UV pilot plant.

(a) (b) (c)

(d) (e)

Figure 93. Pictures of the improved parts of the ozonation pilot plant: a) New 580L contact column reactor; b) Pressurized tank; c) HP pump for nano-bubbles generation; d) Venturi for micro-bubbles injection and e) complete view of the new ozonation pilot plant.

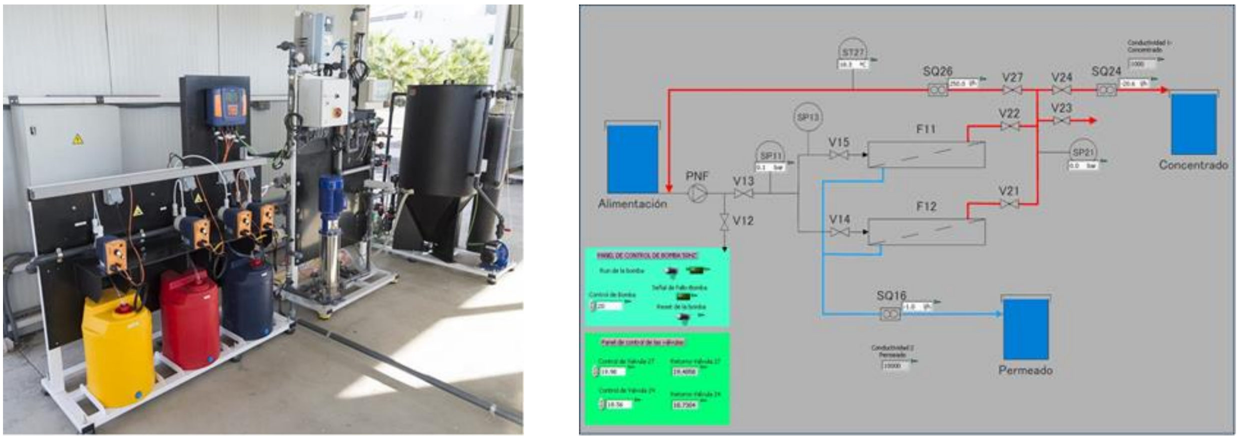
Solar CPC with direct injection of ozone

The solar photo-reactor pilot plant, provided by Arenys Inox S.L., consists of three aluminium anodized CPC modules provided with diffusers inside the tubes to allow the direct injection of ozone in water (coming from the ozone generator previously described). Each module has a surface of 0.28 m^2 with three borosilicate tubes of 50 mm diameter (2.5 mm thickness and 700 mm length). At the inlet of each borosilicate tube there is a stainless-steel gas diffuser AISI-316L (2-micron pore). Water is driven by a Pan World NH50PX 220 V AC and 45 W electromagnetic pump (flow rate of 25 L·min-1). This design contemplates working with one, two or three CPC modules in series, allowing the equipment to operate at different volumes of water from 12 to 25 L. The plant includes data acquisition equipment for pH (HACH), dissolved oxygen, dissolved ozone (model UV-106-W cleaning system, patented MicroSparge™ technology) and temperature (PT-100). The control system SC200 is provided by HACH. The plant includes a thermo-catalytic ozone destructor.

Figure 94. Solar CPC with direct injection of ozone available at PSA facilities

Nanofiltration pilot plant

The nanofiltration (NF) system has two working modes, in series and in parallel. The basic system consisted of three FILMTEC NF90-2540 membranes, connected in parallel, with a total surface area of 7.8 m^2. These polyamide thin-film composite membranes work at a maximum temperature of 45°C, a maximum pressure of 41 bar and a maximum flow rate of 1.4 $m^3 \cdot h^{-1}$, whereas operation pH range is 2 - 11. pH control permits the cleanings and to evaluate the separation of different compounds in the membranes depending on the pH value. A dosing pump is also included for studying the effect of biocide addition. It has a feeding tank of 400 L (Figure 95. a). In 2016, the nanofiltration system was automatized by including electro-valves and automatic acquisition of the different instrumentation signals (flow, pressure, conductivity, temperature, etc.) with the final aim of stablishing a P&ID control system (Labview interface was implemented, Figure 95. b) for controlling the required quality of the permeate flow generated as well as the concentrated stream.



(a) (b)

Figure 95. a) Nanofiltration pilot plant; b) New labview interface for control and automatic operation of the pilot plant.

Photocatalytic generation of hydrogen pilot plant

The pilot plant for photocatalytic hydrogen generation is composed by a closed stainless-steel tank of 10 L connected to a CPC photo-reactor for the simultaneous removal of organic contaminants from aqueous solutions and hydrogen generation (Figure 96). The tank is fitted with gas and liquid inlet and outlet and a sampling port. Two parallel mass flow controllers are used to control the desired N_2 gas flow into the reactor headspace during the removal of O_2 to achieve the reduction conditions as well as to drag the hydrogen produced. A centrifugal pump (PanWorld NH-100PX) with a flow rate of 20 L·min^{-1} is used to recirculate the aqueous slurry from the tank to the tubes of the CPC. The photo-reactor is composed of 16 Pyrex glass tubes (inner diameter 28.5 mm, outer diameter 32 mm, irradiated length 1401 mm) mounted on a fixed platform tilted 37° (local latitude). The total area and volume irradiated is 2.10 m^2 and 14.25 L, respectively. The composition of the gas stream is quantified by a MicroGC 490, using Argon as gas carrier.

(a) (b)

Figure 96. (a) Solar pilot plant for photocatalytic generation of hydrogen; (b) Gas (N_2 and Ar) conduction systems.

Wet Air Oxidation pilot plant

A pilot plant was designed and installed in 2016 as a harsh pre-treatment to reduce the complexity of industrial effluents and reaction time of a subsequent solar advanced oxidation process (AOPs) (Figure 97). This pilot plant operation allows different combinations of temperature and pressure, various proportions of oxygen and nitrogen, oxidants as peroxide and peroxymonosulfate before heating and/or pressurized the system, and the use of different metallic salts as catalyst. The Wet Air Oxidation pilot plant consists of a stainless-steel reactor with a total volume of 1 L, a magnetic stirrer, a breakup disk, liquid reagents injector prepared to operate under 200 bar and a maximum temperature of 300°C, thermo-probe, pressure sensor (until 250 bar) and a cooling-heating jacket, all made of stainless steel. The Wet Air Oxidation pilot plant includes an automatic system of control and data acquisition of diverse parameters such as pressure, temperature, reagents dosses and agitation velocity.

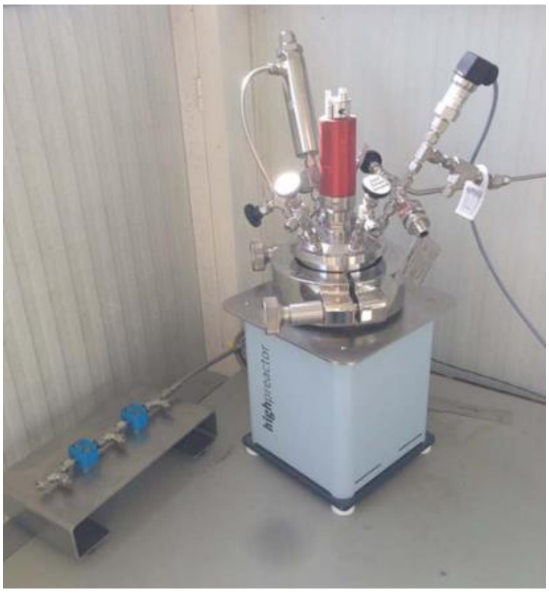


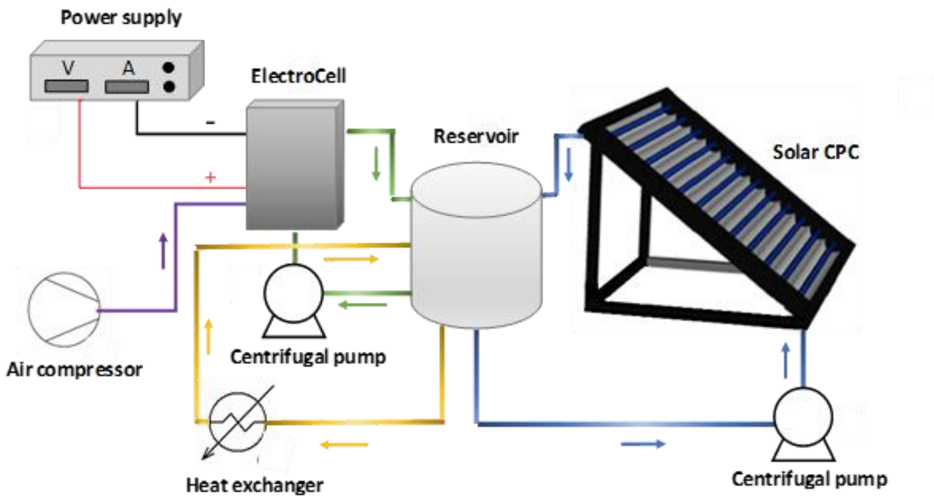
Figure 97. Wet Air Oxidation Pilot plant.

Electro-oxidation pilot plant

Electro-oxidation pilot plant consisted of four undivided commercial electrochemical cells (Electro MP Cell from ElectroCell) conformed by a boron-doped diamond film on a niobium mesh substrate (Nb-BDD) as anode and a carbon-polytetrafluoroethylene (PTFE) gas diffusion electrode (GDE) as cathode, both with 0.010 m^2 effective area single-sides. Electrodes were connected to a Delta Electronika power supply and water from a reservoir is recirculated through the system by centrifugal pumps (Figure 98).

(a)

(b)



(c)

Figure 98. a) Electro-oxidation pilot plant; b) Electrochemical cell of the solar-assisted electrooxidation pilot plant; and c) Schematic diagram of the solar-assisted electrooxidation pilot plant.

Solar UVA monitoring equipment

UV and global solar radiation data monitoring and storage system is composed by different pyranometers (Figure 99), including global solar radiation in the range of 310-2,800 nm (Kipp and Zonen CMP-6 with sensitivity 5-20 $V \cdot W^{-1} \cdot m^{-2}$, max. value: 2000 $W \cdot m^{-2}$), and the global UVA radiation in the range of 300-400 nm (Kipp and Zonen CUV-5 with sensitivity 1 $Mv \cdot W^{-1} \cdot m^{-2}$, max. value: 100 $W \cdot m^{-2}$). Besides this, a spectral photometer with double channel was installed to monitor the solar spectral irradiance at the location of the solar tests. This equipment (AVANTES) has UVA sensors and filters to measure in the whole spectral range of 200 – 1100 nm.

(a) (b) (c)

Figure 99. CUV-5 radiometer (a). View of all solar UV radiometers, horizontal (b) and inclined (c) setup used in the Solar Treatment of Water Unit.

Pilot plants for biological treatment.

A biological pilot plant with a double depuration system (Figure 100) consists of a 60 L feeding tank; three Immobilized Biomass Reactors (IBR) of 20 L each one; and two Sequencing Batch Reactors (SBR) of 20 L each one. These modules use the same reception tank (200 L) as well as pH and dissolved oxygen control systems and electronic equipment. In addition, this plant can be operated in continuous or in batch mode. For the batch operation, two conical decantation tanks (40 L) are used. Data acquisition of three MULTIMETERS (M44 CRISON) is available by means of programmable relays and the main parameters are monitored by a SCADA system.

Figure 100. Biological pilot plant installed at PSA facilities.

Membrane Distillation (MD) / Crystallizer pilot plant.

The pilot plant is composed by a MD module integrated into a system consisting of two hydraulically separated loops, one for the hot solution and the other for the cooling solution. A 150 L PP feeding tank provided with a 3 kW_{th} electrical resistance heating system with a feeding pump (Q_{max} = 1.1 m^3 h^{-1}, T = 80°C) area available. An internal coil thermostated by a chiller (Q_{max} = 15.5 L min^{-1}, 2750 W, range = -10 - 40°C) is incorporated to the tank. Refrigeration is controlled by an external temperature sensor and the cooling pump helps to ensure homogeneity by recirculating it into the tank. Two level ultrasound sensors are installed for measuring the permeate volume produced

(T = -20 - 60°C, P = 0.7-3 bar). The facility has a PLC to register the variables and a control to be able to work for 48 hours. Moreover, the system is prepared to work with acids and bases, and it has a pH regulation system consisting of a tank (HDPE 50 L), a pump (Q_{max} = 20 L h^{-1}, P_{max} = 3 bar, PP), a pH controller and a pH sensor (Range: 0 - 14, P_{max} = 3 bar, T = -5 - 70°C). Finally, the system has a 25 L jacketed borosilicate crystallizer with a stirrer inside (range: 0/30 - 1000 rpm, P: 60 W, material: PTFE) with a pump (flowmeter range: 90 - 900 L h^{-1}). The temperature control is carried out by a control system formed by a chiller (Q_{max} = 15.5 L min^{-1}, 2750 W, range = -10 - 40°C) and an external Pt100 temperature sensor (Figure 101).

Figure 101. MD + crystallizer pilot plant developed by Apria Systems S.L.

Cultivation chamber

The culture crop chamber of 30 m^2 is used for treated wastewater re-use experience since 2014 (Figure 102). This chamber is made of 10 mm polycarbonate thick to avoid ultraviolet radiation supported by white rolled steel (Sendzimir). The shoulder height is 2.5 m with a roof slope of 40 %. The camera consists of four 3 m^2 x 2.5 m^2 individual areas. Each area is equipped with temperature and humidity sensors, and a cooling and heating system. The crop camera is equipped with a global solar radiometer for measuring the incident solar radiation. So, through this probe an opaque plastic cover located on the top of the camera can be automatically fold and re-fold to reduce the incidence of irradiance inside the crop camera. Finally, the roof slope of each area acts as windows which can be automatically opened and closed to favour the airflow inside each area and enhance the efficiency of the temperature control. Sensors' registration (temperature, humidity and solar radiation) and temperature control of each individually area (by the cooling and heating system, windows and top plastic cover) is made by using the Ambitrol® software which permits to keep a comfortable temperature for crops of approximately 25 °C during the different seasons. A new modification was tackled in 2021 consisting in the installation of automatic drip irrigation in the 4 rooms and the cooling system replacement (model HEF3-CAD, Q_{max} =2200 $m^3 \cdot h^{-1}$).

Figure 102. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities.

Optical characterization and solar reflector durability analysis facility - OPAC

The PSA optical characterization and solar reflector durability analysis facility, which is the result of a joint collaborative project between CIEMAT and DLR, has the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. This laboratory allows the evaluation of characteristic optical parameters of solar reflectors and their possible deterioration. The following equipment is available in the laboratory of optical characterization of solar reflectors (see Figure 103.a):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 15° incidence angle, 660 nm wavelength and different aperture angles (3.5, 7.5, 12.5 and 23 mrad).
- One portable specular reflectometer, Devices and Services model MWR, for measuring specular reflectance at 15° incidence angle, 460, 550, 650 and 720 nm wavelength and at different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- One portable reflectometer, PSE model pFlex 2.1, for measuring specular reflectance at 8° incidence angle, 470, 525 and 625 nm wavelength, and 67 mrad aperture angle.
- One portable reflectometer, Aragon Photonics model Condor, for measuring specular reflectance at 12° incidence angle, 435, 525, 650, 780, 940 and 1050 nm wavelength and 145 mrad aperture angle.
- One portable reflectometer, Konica Minolta model CM-700d, for measuring hemispherical and diffuse reflectance at 8° incidence angle, and 400-700 nm wavelength.
- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model SR^2, designed and patented by DLR).
- Spectral Specular Reflectometer S2R for measuring specular reflectance spectra in the wavelength range 280-2500 nm at variable incidence angles of 8-70° and discrete acceptance angles of 7.4, 12.3, 14.8, 20.2, 35.9 and 107.4 mrad (designed and patented by DLR).
- Two Perkin Elmer Lambda 1050 spectrophotometers, with two 150-mm integrating spheres and specular reflectance accessory with 0 to 68° incidence angles (URA).
- One infrared spectrometer, Perkin Elmer FT-IR.

- Nikon D3 camera and 90 cm Cubalite kit for photos of specular surfaces without parasitic reflections.
- Zeiss Axio microscope model CSM 700 (with magnifications of 5, 10, 20, 50 and 100) for finding the profiles and roughness of highly reflective surfaces.
- Parstat 4,000 impedance system to analyse the corrosion of reflector materials.
- General Purpose Optical bench as accessory for the Perkin Elmer Lambda 1050 spectrophotometer with advanced features for mounting optical devices for the development of new measurement instruments.
- Attension Theta 200 Basic tensiometer for static and dynamic contact angle assessment, which is a key parameter to study the performance of the anti-soiling coatings applied to solar reflectors and receiver tubes.

The solar reflector durability analysis laboratory is designed for accelerated ageing tests of these materials with the purpose of predicting in a short time, the behaviour of these materials during their useful lifetime (see Figure 103.b). To do this, the environmental variables producing degradation of solar reflectors when they are exposed to outdoor conditions are applied in a controlled manner, both separately and in combination. The following equipment is available for these accelerated ageing tests:

- Two ATLAS SC340MH weathering chambers for temperature (from -40 °C to +120 °C), humidity (from 10 % to 90 %), solar radiation (from 280 to 3000 nm) and rainfall of 340 L.
- Vötsch VSC450 salt spray chamber with temperatures from 10°C to 50°C (450 L).
- Erichsen 608/1000L salt spray chamber with temperatures from 10°C to 50°C.
- Two ATLAS UV-Test radiation chambers where UV light (with a peak at 340 nm), condensation and temperature can be applied. One of the chambers also includes rain simulation.
- MKF 720 test chamber, where UV light (with a peak at 340 nm) can be applied in combination with a wide range of temperature and humidity conditions.
- Hönle UVA Cube Ultraviolet radiation chamber.
- SC100 heated water bath, to perform the Machu test, according to the Qualitest guideline.
- Vöstch VCC3 0034 weathering chamber to test the material resistance against corrosive gasses (335 L, see Figure 103.b)
- Ineltec CKEST 300 test chamber for humidity and condensation testing with temperatures up to 70°C (300 L).
- Memmert HCP108 weathering chamber to apply humidity (20-95 %) and temperature (2,090 °C) with humidity and 20-160 °C without humidity).
- Two Nabertherm LT 24/12 and LT 40/12 Muffle Furnaces.
- Control Técnica/ITS GmbH sandstorm chamber with wind speeds up to 30 m/s and dust concentrations up to 2.5 g/m³.
- Erichsen 494 cleaning abrasion device to test the degradation due to the cleaning brushes, with several cleaning accessories.
- Taber 5750 linear abraser to check the materials resistance against the abrasion.
- Lumakin A-29 cross-cut tester to analyse the possible detachment of the paint layers.
- Soiling Pipe for simple sand erosion experiments based on DIN 52348. Erodent material hitting the specimen after around 160 cm of free fall under adjustable impact angles (designed by DLR).

- Artificial soiling chamber, equipped with the aerosol generator SAG410/L from TOPAS GmbH and an ultrasonic nebulizer to reach a realistic soiling picture on reflector samples (designed by DLR).
- Several devices for thermal cycles specially designed at the PSA.

(a)

(b)

(c)

(d)

Figure 103. Optical characterization lab (a), durability analysis lab (b), outdoor test bench (c) and outdoor accelerated aging test bench (d) at OPAC facilities.

Along with these labs, there are a series of outdoor test benches for exposing materials to outdoor weather conditions and comparing their degradation with those found in the accelerated ageing tests, to study the effectiveness of special coatings, to optimize the cleaning strategy and to analyse the soiling rate. In addition, two heliostat test benches were recently installed, one to test the influence of blocking on the coatings lifetime and another one to accelerate the reflectors degradation due to UV radiation under outdoor weather conditions. Finally, the laboratory is equipped with accessories necessary for their proper use, such as precision scales, thermo-magnetic stirrer, drier, ultrasonic bath for sample cleaning, tools for reflector samples preparation (cutting and polishing), safety cabinets, instrumentation for measuring pH, conductivity, oxygen, etc.

Experimental Installations for the Evaluation of the Energy Efficiency in Buildings

The Building Component Energy Test Laboratory (LECE) is one of the facilities at the PSA. Its personnel are ascribed to the Energy Efficiency in Building R&D Unit (UiE3) in the CIEMAT Energy Department’s Renewable Energies Division. The UiE3 carries out R&D in integral energy analysis of buildings, integrating passive and active solar thermal systems to reduce the heating and cooling demand. This unit is organised in two lines of research focusing on Energy Analysis in Urban Environments, and Experimental Energy Analysis of Buildings and Building Components. The test facilities described are under the last of these. They integrate several devices with different capabilities as summarised below:

- Test cells. The LECE has five test cells, each of them made up of a high-thermal-insulation test room and an auxiliary room. The test room's original south wall can be exchanged for a new wall to be tested. This makes experimental characterisation of any conventional or new building envelope possible.
- PASLINK Test cell. The Spanish PASLINK test cell incorporates the Pseudo-Adiabatic Shell (PAS) Concept. This system detects heat flux through the test cell envelope by means of a thermopile system and compensates it by a heating foil device. The inner surface of the test room consists of an aluminium sheet which makes it uniform in order to avoid thermal bridging. It also has a removable roof that enables horizontal components to be tested. The cell is installed on a rotating device for testing in different orientations.
- CETeB Test cell. This is a test cell for roofs. The design of this test cell solves some practical aspects related to roof testing, such as accessibility and structural resistance. An underground test room that allows easy access to the test component is used for this.
- Solar Chimney. This was constructed for empirical modelling experiments and validating theoretical models. Its absorber wall is 4.5 m high, 1.0 m wide and 0.15 m thick, with a 0.3-m-deep air channel and 0.004-m-thick glass cover. A louvered panel in the chimney air outlet protects it from rodents and birds. The air inlet is protected by a plywood box to avoid high turbulences from wind. The inlet air flow is collimated by a laminated array so that the speed component is in the x-direction only.
- Single-zone building. This is a small 31.83 m^2 x 3.65 m high simple single-zone building built in an area free of other buildings or obstacles around it that could shade it, except for a twin building located 2 m from its east wall. Its simplicity facilitates detailed, exhaustive monitoring and setting specific air conditioning sequences that simplify its analysis for in-depth development and improving energy evaluation methodologies for experimental buildings.

The PSE ARFRISOL C-DdIs are fully instrumented Energy Research Demonstrator Office Building Prototypes which are in use and monitored continuously by a data acquisition system. The CIEMAT owns 3 out of 5 of these "Contenedores Demostradores de Investigación, C-DdIs" (Research Energy Demonstrators Building Prototypes), built under the ARFRISOL Project. Each of them is an office building with approximately 1,000 m^2 built area. One of them is at the PSA and the others in different locations representative of Spanish climates. These C-DdIs are designed to minimize energy consumption by heating and air-conditioning, whilst maintaining optimal comfort levels. They therefore include passive energy saving strategies based on architectural and construction design, have active solar systems that supply most of the energy demand (already low), and finally, have conventional auxiliary systems to supply the very low demand that cannot be supplied with solar energy, using renewable energy resources, such as biomass insofar.

These prototypes were built for high-quality measurements recorded during monitoring to support research activities on energy performance assessment of the building fabric, thermal comfort, building energy evaluation and both active and passive systems integrated in the buildings.

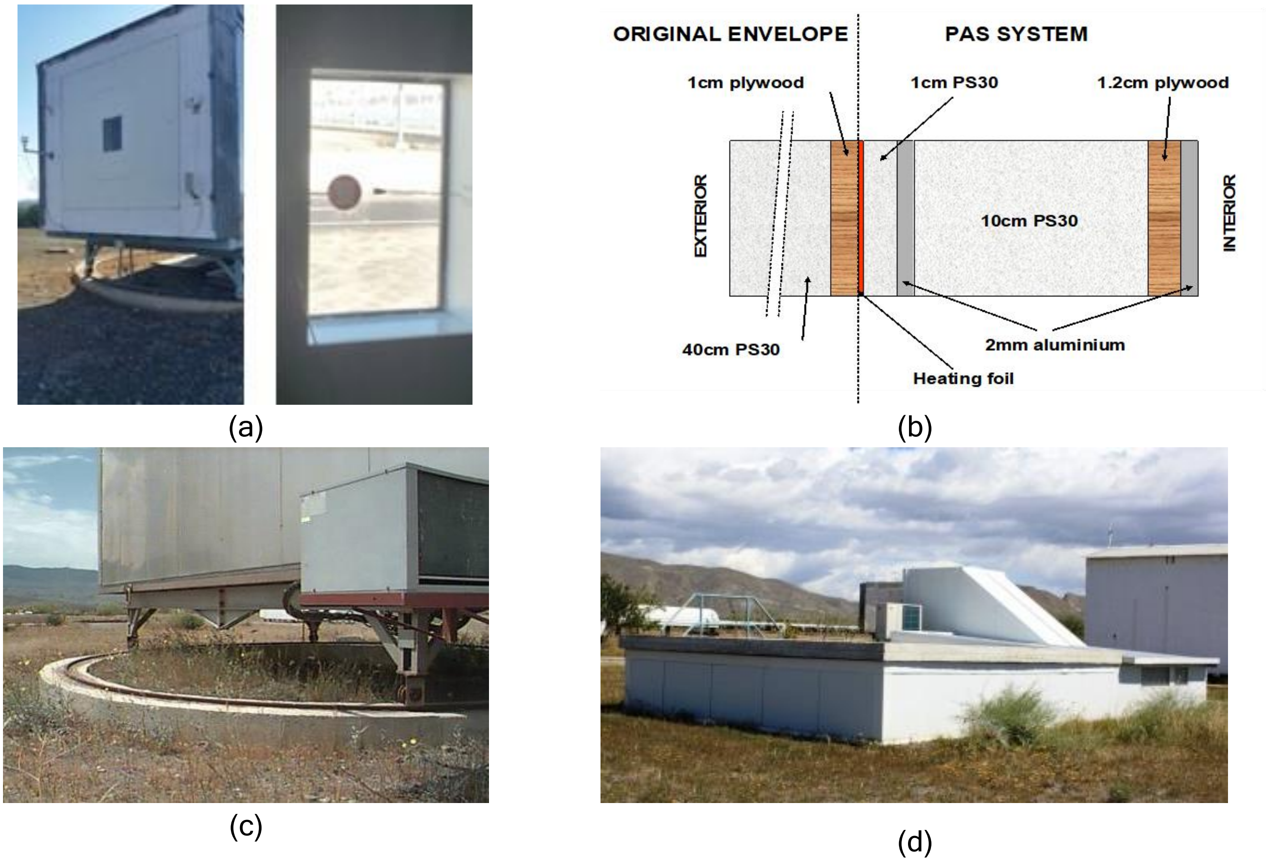


Figure 104. (a) CIEMAT's PASLINK test cell carrying out a thermal test of a electrocromic window (left: outdoors; right: indoors), (b) Schematic drawing of the PAS system, (c) Detail of the rotating device, (d) Exterior of the CETeB Test cell.

(a) (b)

(c) (d)

Figure 105. (a) ARFRISOL Building Prototype in use, (b) Solar Chimney , (c) Reference single-zone building, (d) Ventilated façade tested in a Test Cell. Configurations with dark external face.

14 Laboratories

Laboratory for the geometrical characterization of solar concentrators - GeoLab

The concentrators used in solar thermal systems (heliostats, parabolic-trough collectors, parabolic dishes, Fresnel lenses, etc.) require high precision concentration of the solar radiation for it to be suitable and for most of it to fall upon the receiver component (receiver tubes in parabolic-trough collectors, receivers in tower systems, parabolic dishes, Fresnel lenses, etc.). This laboratory has a specific activity line for the geometric characterization of these concentrators. Photogrammetry is used to quantify the optical quality of:

- Parabolic-trough collector facets
- Parabolic-trough collector modules
- Heliostat facets
- Heliostats
- Fresnel lenses and reflectors
- Parabolic dishes
- Structural frames
- …

Photogrammetry consists of three-dimensional modelling of any object from photographs that capture it from different angles. Based on these photographs, the three-dimensional coordinates (x, y, z) can be calculated for the points of interest on the object being modelled. Photogrammetry modelling is precise up to 1:50000 (precisions on the order of 0.1 mm for parabolic-trough collector facets and 0.6-0.7 mm for 12-m-long parabolic-trough modules).

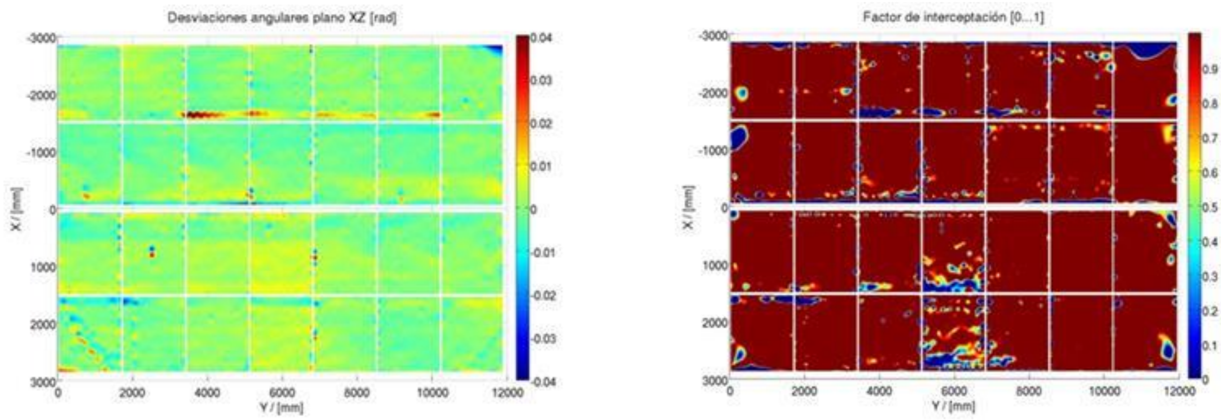
The equipment allocated to this activity at PSA is composed of:

- CANON EOS5D MarkII 22-Mpixel Camera.
- CANON EF 20 mm f/2.8 USM and CANON EF 24 mm f/2.8 USM lenses.
- Photomodeler Scanner 2017 photogrammetry software.
- LEYCA P20 laser scanner

Additionally, a software package for model analysis and calculation of relevant parameters for 2D and 3D geometries in the MatLab environment was developed in house.

Among the parameters that can be calculated from the model built by photogrammetry are:

- Deviations of real from theoretical surface on coordinates x, y, z.
- Gravity deformation between different concentrator orientations.
- Angular deviation from the normal vector to the surface compared to the theoretical normal vector.
- Deviation of reflected rays on the reflective surface of the module compared to the theoretical concentrator focus.
- Intercept factor.
- (Calculation of other relevant parameters by request).



(a) (b)

Figure 106. Angular deviations (a) and intercept factor (b) of a parabolic-trough collector module analysed by photogrammetry.

Radiometry laboratory – RadLab

The activity line devoted to Radiometry came out from the need to verify measurements of highly important radiometric magnitudes associated with solar concentration. These magnitudes are solar irradiance ("flux" in the jargon of solar concentration) and surface temperature of materials (detection by IR). At the PSA, different systems are used to measure high solar irradiances on large surfaces. The basic element in these systems is the radiometer, whose measurement of the power of solar radiation incident on the solar receiver aperture depends on its proper use. The measurement of this magnitude is fundamental for determining the efficiency of receiver prototypes evaluated at the PSA and for defining the design of future central receiver solar power plants. Calibration of radiometers is performed in a specific furnace for this purpose.

Figure 107. View of the PSA Radiometry equipment.

The calibration of the reference radiometer is radiant calibration referenced to blackbody simulators as source standards. The calibration of the reference radiometer is transferred to the commercial sensors by comparison in a calibration furnace that uses a graphite plate that radiates homogenously and symmetrically when an electrical current passes through it. The calibration constant obtained with this method translates voltage to irradiance on the front face of the sensor. The accuracy of gages calibrated in this way is within ±3 % with repeatability of ±1 %. A black body can be used as a source of thermal radiation for reference and calibration of IR devices (infrared cameras and pyrometers) that use thermal radiation as the means of determining the temperature of a certain surface.

The equipment associated to this activity also includes three black bodies used as references for calibrating IR sensors devoted to temperature measurement with guaranteed traceability between 0 and 1700°C:

- The MIKRON 330 black body is a cylindrical cavity which can provide any temperature from 300 °C to 1,700 °C accurate to ±0.25 % and a resolution of 1 °C. Its emissivity is 0.99 in a 25-mm-diameter aperture.
- The MIKRON M305 black body is a spherical cavity that can supply any temperature between 100 °C and 1,000 °C accurate to ±0.25 and with a resolution of 1 °C. Its emissivity is 0.995 in a 25-mm-dia. aperture.
- The MIKRON M340 black body is a flat cavity and can provide any temperature from 0 °C to 150 °C accurate to ±0.2 °C and a resolution of 0.1 °C. Its emissivity is 0.99 in a 51-mm-aperture.

These black bodies have a built-in PID control system, and the temperature is checked by a high-precision platinum thermocouple.

Figure 108. IR sensor calibration using a black body.

Laboratory for the assessment of the durability and characterization of materials under concentrated solar radiation - MaterLab

The activity line of this Laboratory is focused on the study and evaluation of how the concentrated solar radiation affects the performance and durability of materials. This is especially important for materials used for central receivers, thus requiring an accelerated ageing to study the durability of the most critical components of solar thermal power plants, not only absorbent materials, but also surface treatment and coatings that increase their absorptance. It is therefore necessary to find out and study the mechanisms of the physical degradation and breakage of these materials at high temperatures under concentrated solar radiation.

The equipment associated to this activity is composed of devices located indoor, apart from several solar-dish concentrators located close to the PSA solar furnaces building. The indoor devices are devoted to the metallographic preparation and the analysis of test pieces treated with concentrated solar radiation and eventually thermal cycling for accelerated aging, and characterization of solar test by thermogravimetry. These devices are inside the Solar Furnaces control building and located in four rooms, each of them dedicated to different kind of analyses:

- The Metallography Room
- The Microscopy Room
- The Thermogravimetry Room
- The Thermal Cycling Room
- The Electronic microscope Room

The laboratory equipment located in these rooms is listed below.

Metallography Room

This room is equipped for the metallographic specimen preparation and the particle size determination:

- Automatic cut-off machine: Struers Secotom
- Manual cut-off machine: Remet TR60
- Mounting press: Struers Labopres-3
- Vacuum impregnation unit: Struers Epovac
- Polisher: Tegrapol-15 automatic with Tegradoser-5 dosing system
- Metallographic polisher 2 plates: LS1/LS2 (Remet)
- Grinder: Remet SM1000
- Ultrasonic bath: Selecta Ultrasons-H 75 °C with heater
- Fume cupboards: Flores Valles VA 120 960 M-010-02
- Power Source programmable: Iso-Tech IPS 405 for electrochemical attack
- Analytical sieve shaker: Retsch AS 200 Control (Sieves: 20, 10, 5, 2.5 and 1.25 mm, and 710, 630, 425, 315, 250, 160, 150, 90, 53 and 32 µm)
- Digital
- Camera with reproduction table

Figure 109. View of the Metallography Room in the Solar Furnaces building.

Microscopy Room

Microscopy, hardness and solar reflectance measurement equipment for optical and surface characterisation of materials is available in this room:

- 3D Optical Surface Metrology System: Leica DCM 3D
- Leica DMI 5000 optical microscope with Leyca-IM50 image acquisition system and motorized table.
- Olympus optical microscope Union MC 85647.
- 410 Solar Portable Reflectometer
- ET100 IR Portable Emissometer
- Struers micro hardness tester Duramin HMV-2 with visualization system and software micro-Vickers hardness tester HMV-AD 3.12.
- Manual hardness tester
- Surface Finish Measuring Unit ZEISS Surfcom 480 with data processor
- Balance: Mettler E2001/MC max 60 kg
- Balance: Mettler Toledo classic max 320 g/min 10 mg

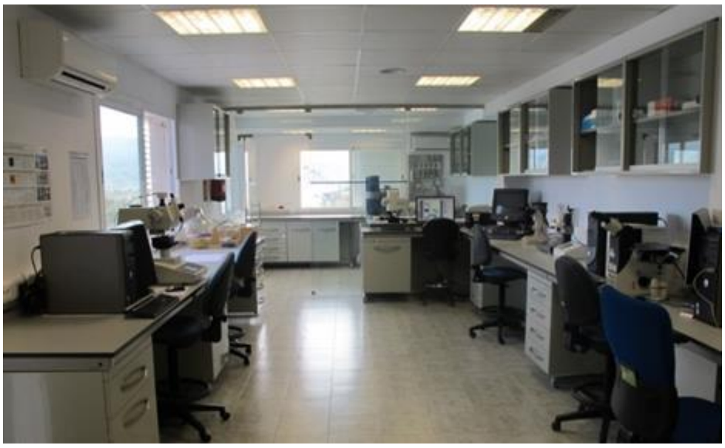
Thermogravimetry Room

The thermogravimetric Balance SETSYS Evolution18 TGA, DTA, DSC (temperature range from ambient to 1,750 °C) was redesigned some years ago to be prepared for Hydrogen production test including the equipment and connections needed. This TGA-DTA-DSC balance is equipped with a compact recirculating cooler (Julabo FC1600T) and a thermostatic line to 200 °C, with a security box for tests in presence of H_2, and adapted to connect a controlled evaporator mixer and a with an external connection to connect a microGC simultaneously to the equipment. Its design allows different possibilities of tests:

- Tests under any gas atmosphere up to 1,750 °C, including:
- Tests under pure Hydrogen atmosphere
- Tests under pure Oxygen atmosphere
- Tests under H_2O steam with other gases simultaneously.
- Tests under corrosive atmosphere up to 1,000 °C

This room is also equipped with:

- CEM System (Controled evaporator mixer system) for steam supply.
- Fixed Gas Detector: Dräger Polytron SE Ex, with a control system Regard 1.


(a)


(b)

Figure 110. View of the Microscopy Room (a) and the thermogravimetric balance inside of its room (b).

Thermal Cycling Room

It includes the instrumentation necessary for thermal cycling:

- two muffle furnaces
- a high-temperature kiln
- a weathering chamber
- an air-cooled volumetric receiver test loop and associated instrumentation

Laboratories associated to line-focus solar concentrators

HEATREC and RESOL

There are two test benches at PSA for the testing of linear receivers: a) a test bench called HEATREC (see Figure 111.a), for measuring heat loss of single receiver tubes under indoor laboratory conditions, and b) an outdoor test bench called RESOL (see Figure 111.b), for measuring optical efficiency of single receiver tubes under natural solar radiation. Heat loss measurements can be done in HEATREC under vacuum conditions to avoid convection outside the glass tube, thus obtaining a more uniform temperature along the receiver section and looking for the heat loss by radiation. In addition, it is possible to determine heat loss at different vacuum levels in the space between the metallic absorber tube and the glass envelope. The emissivity of the selective coating can be then inferred from these thermal loss measurements.

HEATREC device allows to characterize heat losses of receiver tubes with an inner diameter greater than 62 mm and a tube length lower than 4.5 m. Measurements can be performed for absorbing temperature ranging from 100 °C to 500 °C. The vacuum in the test chamber can be set up to around 10^{-2} mbar. RESOL is currently configured to measure standard receiver tubes for parabolic troughs, i.e., tubes 4060 mm-long and with absorber tube diameter of 70 mm.

(a) (b)

Figure 111. View of the HEATREC test chamber to measure heat losses in solar receiver tubes (a) and RESOL test bench to measure receiver's optical efficiency (b).

The optical efficiency tests performed with RESOL are based on the evaluation of the slope of the temperature of a fluid (water) circulating inside the receiver tube vs the time during an interval of steady state solar radiation when heat losses are null. The optical efficiency is calculated from an energy balance of the system. The test provides in one measurement the receiver optical efficiency, i.e., the combined value of the absorptance and transmittance of the receiver tube.

Both HEATREC and RESOL, are equipped with tools and devices for proper manipulation and monitoring of receiver tubes.

Advanced Optical Coatings Laboratory - OCTLAB

This laboratory line is devoted to the development and complete study of new selective coatings for absorbent materials used in solar concentrating systems at medium and high temperature (up to 700°C), as well as coatings for glass covers (anti-reflective, anti-soiling. etc) used in some receiver designs, such as receiver tubes in parabolic-trough collectors. The equipment devoted to this activity line is sufficient to characterize and evaluate coating developments, and to asses the behaviour of other treatments available on the market or developed by other public or private institutions. The equipment associated to this line may be also used for optical characterization of solar reflectors, thus complementing the equipment specifically devoted to the activity line of testing and characterization of solar reflectors.

A summary of the equipment available for advanced optical coatings is given below:

- Perkin Elmer LAMBDA 950 Spectrophotometer equipped with a 150 mm integrating sphere (Figure 112).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrated sphere manufactured by Pike (Figure 112).
- LEICA DM4 M optical microscopy with image acquisition system and software for image analysis (Figure 112).
- KSV CAM200 goniometer for measuring static contact angles (Figure 112).
- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (Figure 112).
- BROOKFIELD LVDV-I+ Viscometer.
- BRUKER DektakXT stylus profilometer with optical camera and software for surface analysis (Figure 112).
- TABER linear abrader model 5750, equipped with different types of abrasive materials to measure the abrasion resistance of coatings and materials (Figure 112).
- TABER oscillating abrasion tester, Model 6160, to measure the relative abrasion resistance of the materials to surface abrasion and / or marring produced by sand movement. Different types of standardized sands are available (Figure 112).
- Dip Coating machine for producing thin films. This machine controls the speed of substrate withdrawal from solution using a programmable high-precision motor and coatings up to 40cm long can be prepared.
- Kilns. There are three kilns for thermal treatment:
  - 120x100x300 mm^3 kiln with a maximal temperature of 1,200 °C.
  - Controlled atmosphere kiln with a maximal temperature of 800 °C.
  - 500x400x600 mm^3 forced convection kiln with a maximal temperature of 550 °C.

Figure 112. Advanced optical coatings laboratories equipment.

Porous media laboratory for solar concentrating systems - POMELAB

The porous media laboratory located in CIEMAT-Moncloa (Madrid) comprises three main facilities, and some other techniques for the characterization of porous materials used for central receiver systems with air as heat transfer fluid.

1) Thermal characterization of volumetric absorbers.

Its main component is a test bench designed for the thermal test of new volumetric absorbers and configurations and its ageing in steady and dynamic conditions. The main components installed in this test bench (Figure 113) are:

- A 4 kWe solar simulator made up of a Xenon lamp and a parabolic concentrator that can reach fluxes of up to 1,500 kW/m^2;
- Receiver sub-system: with 24 K-type thermocouples, 2 surface thermocouples and an infrared camera;
- Helicoidal Air-Water Heat Exchanger sub-system: with 4 PT100 sensors, a water mass flow-rate measurement, a water pump and 2 surface thermocouples; and
- Extraction system: with 1 k-type thermocouple, 1 PT100 sensor, an air mass flow-rate measurement, and an air blower.

This test bench has the flexibility to study the extinction coefficient of different mediums, which can be used as a tool to approximate radiation analysis in semi-transparent mediums following the Bouger's law.

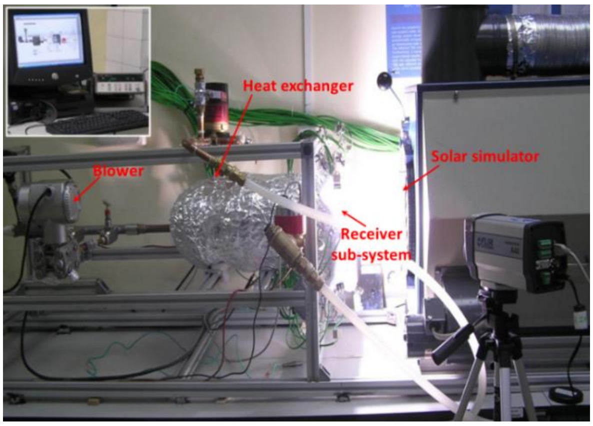


Figure 113. Test bench for volumetric receiver testing

2) Measurement of the pressure drop up to 300 °C.

This facility measures the pressure difference across porous materials, such as volumetric absorbers or filler materials, for different fluid velocities. Moreover, it can measure the pressure difference at ambient temperature and for air temperatures up to 300 °C.

Then the main properties described by the Forchheimer extension to Darcy's law are derived: viscous permeability coefficient and, inertial permeability coefficient. The main components are:

- Sodeca Blower with velocity control
- Hastinik ball valve of 1 ½".

- Airflow anemometer
- Nabertherm heating resistor
- Honeywell pressure difference-meter

Moreover, different techniques have been developed for the evaluation and measurement of several important geometric parameters of porous materials such as the porosity and specific surface area.

Figure 114. Test bench for pressure difference measurement with configuration up to 300 °C.

Laboratory of Thermal Energy Storage

In order to support the R&D&I activities at the PSA on the feasibility of materials as storage media, the following set-ups are available:

HDR: Small vertical oven under ambient air with a cylindrical ceramic cavity where the sample can be allocated. Its upper part can be covered with a double glass trap (Fig. 2. right), for condensing the evolved gases. It allows performing consecutive thermal cycles up to 500 °

C and isothermal stand-by periods. Sample temperature can be monitored and sample mass can be in the range of 1-10 g.

Figure 115. HDR.

SUBMA: Small closed device located inside a furnace. It can accommodate samples of 30-40 g that can be tested under inert atmosphere (N_2, Ar). During the tests, furnace temperature and gas flow can be controlled and sample temperature can be monitored. It allows performing thermal cycles up to 500 °C and isothermal stand-by periods.

Figure 116. SUBMA.

AgH: Oven under ambient air atmosphere with an accurate control of both heating and cooling rates. It allows performing consecutive thermal cycles up to 350 °C and isothermal stand-by periods. Sample temperature can be monitored and sample mass can be in the range of 10-20 g.

Figure 117. AgH.

PSA Desalination Laboratory

Bench-Scale Unit for Testing Membrane Distillation applications in Air-Gap, Permeate-Gap and Direct Contact Configurations

The installation consists of a test plant (Figure 118) that can be used for evaluating direct-contact, air-gap or permeate-gap membrane distillation. It can use plate and frame or hollow fibre modules. The plate and frame modules are made of polypropylene and designed so that the membrane can be replaced very easily. They have a condensation plate on the cold side to operate on air-gap configuration but it can be closed at the bottom to operate on permeate-gap keeping the distillate inside the gap or spared to operate on direct-contact mode. There are two modules, with effective membrane surface areas which measure 25x15 cm^2 and 11x7 cm^2. The hollow fibre module is 50 cm long and 4 cm wide.

Figure 118. Bench-scale unit for testing membranes on isobaric MD.

The installation has two separate hydraulic circuits, one on the hot side and another on the cold side. On the hot side, there is a tank of 80 litres equipped with an electric heater (3 kW) controlled by a thermostat (90 °C maximum), and circulation is made from the storage and the feed side of the module by a centrifugal pump. On the cold side, there is a chiller (800 W at 20 °C) controlled by temperature and water is circulated between a cold storage of 80 litres and the module. The circuit is heat insulated and fully monitored for temperature, flow rate and pressure sensors, connected to a SCADA system.

Bench-Scale Unit for Flat Sheet Membrane Distillation Testing

The facility is a high precision laboratory grade research equipment (Figure 119) designed for testing fundamental and feasibility test trials on membrane distillation. It possesses the following unique features that are essential for representative and scalable results:

1) Cell format with representative flow distribution. The plate and frame cell size (effective membrane surface 220 mm x 150 mm) is sufficient for flow distribution and regime to be applicable to full-scale MD technology.

2) Smaller plate and frame cell (effective membrane surface 100 mm x 60 mm) and HF cell (50 cm long) for testing materials and solutions.

3) Adjustable MD channel configuration to all channel variants (PGMD, AGMD, DCMD, VAGMD).

4) Temperature precision of 0.5 °C.

5) Driving force temperature difference controllable.

6) Fully automated control system and large range of possible parameter settings by touch screen PLC.

Figure 119. Bench-scale unit for testing MD with flat-sheet membranes.

Bench-Scale Unit for Tests with 2-stage Forward Osmosis and Pressure-Retarded Osmosis

The installation consists of a test bed with two small plate and frame modules of forward osmosis (FO) which can be connected in series or parallel (Figure 120). There is, therefore, one pump for the draw solution and two for the feed solution, each with variable flow and flow-rate measurements. The hydraulic circuit has been modified so that the modules can be operated in pressure-retarded osmosis (PRO) mode. For that purpose, steel pipes and a high-pressure pump (3 L/min; up to 17 bar) are installed in the draw side, and cells with operational pressure up to 15 bar are used. The cells each have a total effective membrane area of 100 cm^2, and hydraulic channels in zigzag 4 mm wide and 2 mm deep. The system uses one container for the draw solution and two for the feed solutions, each placed on a balance in order to measure changes in the mass flow rates of the draw solution and the feed solution of each cell. The containers have an automatic dosing system to keep the salinities constant. The system has two conductivity meters for low salinity and one for high salinity, as well as pressure gauges in each line and temperature readings.

Figure 120. Bench-scale unit for testing FO and PRO.

PSA Water Technologies Laboratory - WATLAB

Within the scope of the SolarNova Project funded by the Ministry of Science and Innovation within the Special State Fund for Dynamization of Economy and Employment (Fondo Especial del Estado para la Dinamización de la Economía y el Empleo – Plan E) a new laboratory was built in 2009. Since them, acquisitions of new instrumentation have been done within the SolarNova Project. The PSA water technologies laboratory consists of 200 m^2 distributed in six rooms: (i) a 30 m^2 room for chemicals and other consumables storage. It is organized on numbered and labelled stainless steel shelving with refrigerators and freezers for samples and standards keeping; ii) A 17-m^2 office with three workstations where visiting researchers can analyse the data from the experiments carried out at the PSA. In addition, (iii) 4 technical rooms are also part of the laboratory and are listed and described below:

- General laboratory
- Chromatography laboratory
- Microbiology laboratory
- Microscopy laboratory

General laboratory

The main laboratory is 94 m^2 (Figure 121). It is equipped with four large work benches, two gas extraction hoods, two heaters, a kiln, ultrasonic bath, three centrifuges, three UV/visible spectrometers, a fluorimeter, a vacuum distillation system, ultrapure water system, pH meters (three of them portable), turbidimeter, luminometer, conductivity-meter (one portable), a precision-scale table with two precision scales, an electronic scale and a mini-chiller. In addition, it has a centralized gas distribution system, UPS, three-pin plugs connection and safety systems (extinguishers, shower, eyewash, etc.). The laboratory is also equipped with suspended and supported activated sludge respirometry (BMT) toxicity and biodegradability measurement devices and required equipment for the analysis of biological oxygen demand (BOD), toxicity and phytotoxicity tests (acute and chronic) and chemical oxygen demand (COD). In addition, a Jar-Test system is also available for the optimization of physicochemical separation studies.

Figure 121. General view of the new PSA Water Technologies Lab.

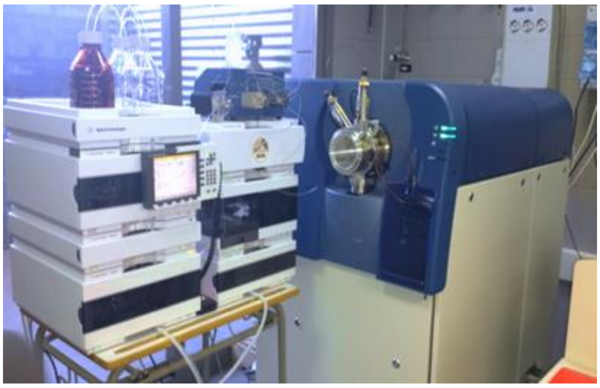
Chromatography laboratory

This laboratory (Figure 122.b) is equipped with three high performance liquid chromatographs with diode array detectors (one of them also with a florescence detector,HPLC-DAD,UPLC-DAD, UPLC-DAD-FLD) with quaternary pumps and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which allows working with low concentration of pollutants (Figure 122.c) and two ion chromatographs (Figure 122.a): one configured for isocratic analysis of amines and cations (Metrohm 850 Professional IC), and another for gradient analysis of anions and carboxylic acids (Metrohm 872 Extension Module 1 and 2) with conductivity detectors (Methrom 850 Professional IC detector). Two total organic carbon (TOC) analysers by catalytic combustion at 670 °C and total nitrogen (TN) analyser with autosampler, are also available. In addition, an AB SCIEX TripleTOF 5600+ was acquired to detect and identify non-targeted or unknown contaminants present in wastewater or generated (transformation products) during the water treatments: Triple TOF by a DuoSpray Source combining Turbo Ion Spray and APCI (Atmospheric Pressure Chemical Ionization) modes. Besides, the system includes metabolomics statistical package to analyse multiple samples from multiple experiments and identified possible chemical and biological markers (Figure 122.d). In 2021, an Ultra Pressure Liquid Chromatograph coupled to a triple quadrupole-linear ion trap mass spectrometer SCIEX EXION (SCIEX Triple Quad 7500 System) was acquired (Figure 122.e). This equipment consists of a binary pump for working in constant flow or constant pressure modes, column oven (thermostated from 10 to 80 °C), automatic autosampler (for more than 100 samples), mass spectrophotometer, UPS, nitrogen generator (Peak Infinity 1032), data station (SCIEX OS).

(a)

(b)

(c)



(d)

(e)

Figure 122. (a) Metrohm Ion chromatograph System. (b) General view of the chromatography lab at PSA facilities. (c) Agilent Ultra-fast UPLC-DAD analyzer. (d) AB SCIEX TripleTOF 5600+ equipment. (e) AB SCIEX 7500 QTRAP Ready LC/MS.

Microbiology laboratory

47-m^2 microbiology laboratory with biosafety level 2 (Figure 123) is equipped with five microbiological laminar flow (class-II) cabins (four double and one simple), three autoclaves, four incubators (one with temperature ramp), a fluorescence and phase contrast combination optical microscope with a digital camera incorporated. Besides, automatic grow media preparer and plaque filler, two filtration ramps with six positions and a dishwasher are available.

Figure 123. General view of the microbiology lab at PSA facilities.

This lab is also equipped with ultra-fast real-time quantitative PCR (Polymerase Chain Reaction) equipment, fluorospectrometer and NanoDrop spectrophotometer for genetic quantification of micro-volumes. A 'Fast Prep 24' was also acquired; it is a high-speed benchtop homogenizer for lysis of biological samples, needed for further analyses of genetic material samples. Homogenizer stomacher 400 Comecta equipment was acquired to blend food samples, stirring and storing in a reproducible way without any risk of cross contamination between samples.

Microscopy laboratory

The microscopy laboratory has two optical microscopes: i) a fluorescence and phase contrast combination optical microscope and, ii) a FISH microscope (Leyca) with a fluorescence module to develop the FISH (Fluorescent in situ hibrydation) technique for visualization of DNA hibrydation with specific probes in live cells used for monitoring key microorganisms within a heterogeneous population (Figure 124. Optical microscope for FISH technique).

In addition, the system is completed with a station for photographic documentation, consisting on a UV-trans-illuminator to detect and visualize DNA, RNA and proteins. It also includes a documentation station with a camera to take images of DNA, RNA and proteins.

Figure 124. Optical microscope for FISH technique

PSA radiometric net

The PSA has had a meteorological station since 1988, primarily for measuring integral solar radiation (global, direct and diffuse radiation) but also for other generic meteorological variables (temperature, wind speed and direction, relative humidity and atmospheric pressure, accumulated precipitation, etc.). The old station was completely remodelled in 2005 following the strictest requirements of quality and precision in the measurement of solar radiation according to the Baseline Surface Radiation Network guidelines. This station is called METAS station since 2012 (Figure 125).

The METAS station instruments are in the highest range of solar radiation measurement. All the radiation sensors are ventilated-heated and have a temperature measurement sensor. This equipment provides the best information on solar radiation and more general atmospheric variables and can be used for filtering input data and validating spectral models. They are used for:

- Measurement of the terrestrial radiation balance. Incoming and outgoing shortwave and long-wave radiation is measured at 30 m
- Solar radiation component characterization: (global, direct and diffuse)
- UV and PAR spectral bands
- Vertical wind profile: wind speed and direction at 2, 10 and 30 meters
- Vertical temperature and humidity profile at 2 and 10 meters
- Miscellaneous weather information: rain gauge, barometer and psychrometer

Figure 125. General view of METAS station.

Additionally, a set of complementary structures for the calibration of radiometers has been installed near to this meteorological station following the standardized international procedures (ISO-9059 and ISO-9846). On the one hand, a high-performance tracker with the possibility of carrying 2 reference pyrheliometers (absolute cavity radiometer PMOD PMO6-CC) and a total of 19 field pyrheliometers have been installed close to METAS; on the other hand, 3 calibration benches, with capacity to carry 20 pyranometers each one, have been placed 50 meters away from METAS (Figure 126). These facilities are operated in collaboration with the Instrumentation Unit.

Figure 126. Calibration facilities.

Since the beginning of 2018 there are seven new radiometric stations fully operational all around the PSA area (Figure 127). All these stations are equipped with first-class pyranometers and pyrheliometers, 2-axis solar trackers and have data acquisition systems Campbell CR1000 (METAS has a CR3000).

Figure 127. PSA radiometric stations.

15 Events

13th January 2022

Lecture

Lecture given by Sixto Malato in “Master universitario en Gestión Sostenible y Tecnologías del Agua” at the Univ. of Alicante.

9th February

Round Table

E. Zarza participated as panellist in the round table held on-line and organized by ATA Insights and PROTERMOSOLAR with the title: “The opportunities of the new 200MW concentrated solar power (CSP) tender in Spain”.

17th February

Lecture

Lecture given by Diego Alarcón, “Recursos en línea y modelos de simulación para instalaciones de energía solar térmica”, within the Máster en Energías Renovables of Universidad Internacional de Valencia.

21st February

Workshop

Meeting of the Community of Practice of Case Study 2 of the WATER MINING project.

21st March 2023

Lecture

Lecture given by Esther Rojas entitled “Almacenamiento Térmico” in the online course “Tecnologías, Operación y Aplicaciones del Almacenamiento de Energía en Sistemas Eléctricos organized by SECARTYS & CIEMAT.

25th March

Lecture

Guillermo Zaragoza gave an invited lecture “Solar-powered membrane distillation for saline water treatment” at the 1st International Conference on Advances in Water Treatment and Management (ICAWTM-22) in Gandhinagar (India).

25th March 2022

Workshop

The Solar Treatment of Water Research Unit organized the “Segunda serie de Talleres para “stakeholders” del proyecto AQUACYCLE. “Planes de acción en regeneración de agua residual tratada” at Plataforma Solar de Almería - CIEMAT

30-31st March 2023

Lecture

Lectures given by Rocío Bayón entitled “Energía Solar Térmica and Almacenamiento Térmico” inº the Master de Materiales avanzados, nanotecnolgía y fotónica of Universidad Autónoma de Madrid.

1st April 2022

Lecture

Lecture given by Sixto Malato "Regeneración de aguas contaminadas mediante tratamientos avanzados para cerrar el ciclo integral del agua: una aproximación utilizando radiación solar" in "Escuela Nacional en Procesos Ambientales (ENPA 2022)", Univ. Guanajuato (Mexico).

7th April

National conference

Participation of E. Zarza as guest speaker in the Joint National Event organized by ODTU-GUNAM at the congress SOLAREX-14th held at Istambul (Turkey) from April 7th to 9th. The title of the invited talk was "CST Applications and Spanish experience".

13th April

Seminar

E. Zarza gave an on-line invited talk on "Concentrating Solar Thermal Technologies and PSA Activities&Facilities". This Seminar was organized by the Iranian University of Isfahán in order to check possible research collaborations between Iranian researchers and PSA.

20th April 2023

Lecture

Lecture given by Esther Rojas entitled "Sistemas de Almacenamiento Térmico" in the online course on trianing on "Sistemas Solares Térmicos de Concentración: tecnologías, aplicaciones e instalaciones experimentales en la PSA organized by CIEMAT-CARTIF.

5th May 2023

Lecture

Lecture given by Esther Rojas entitled *Almacenamiento Térmico* in the online course *Especialista en Almacenamiento Energético* organized by ITE.

17th May 2022

Lecture

Lecture given by Sixto Malato "Investigación en tratamientos avanzados para regeneración de aguas: estado actual" in "Jornada Life AMIA" in CEBAS-CSIC, Murcia.

7th-9th June

International visit

Visit to the PSA of Dr. Eng. Mohamed Barbouche, from the Research and Technologies Centre of Energy (CRTEn), Tunisia, in order to exchange experience about solar technologies, to discuss eventual cooperation projects and to visit PSA experimental facilities.

15th June

Presentation

E. Zarza made a presentation on "Límites prácticos a la descarbonización total del sistema eléctrico español" at the Seminar organized by CIEMAT, PROTERMOSOLAR and SOLARCONCENTRA at the energy fair GENERA-2022 (Madrid).

30th June 2023

Lecture

Lecture given by Esther Rojas entitled "Overview of current R&D&i activities on Thermal Energy Storage for Power Generation" in the Summer Week del Master europeo Erasmus Mundus Joint Master Degree (EMJMD) on Sistemas Descentralizados de Energia (DENSYS), organized by Universidad Politécnica de Cataluña.

6th July

Round Table

J. Blanco and E. Zarza participated as panellist in the Round Table "La I+D en Tecnologías Solares Térmicas de Concentración" included in the HORIZON-STE Joint Industry and R&I National Event organized by CIEMAT and ESTELA, and held at CIEMAT premises in Madrid.

12-14th July 2022

National School

Isabel Oller gave the lecture "Procesos de Oxidación Avanzada para la Regeneración de Aguas: eliminación de contaminantes de preocupación emergente e inactivación de patógenos" in the XXIII Curso de verano de la UAL: Nuevas fuentes de agua: desalación y regeneración hacia la sostenibilidad del ciclo integral del agua in Almería (Spain).

21st July

Lecture

Guillermo Zaragoza gave an invited lecture "The role of membrane distillation in the Water-Energy-Food" in the 11th International Seminar on Thermodynamic Engineering of Fluids organized by Universitat Rovira i Virgili (Tarragona).

30th of August-1st September 2022

International School

Isabel Oller and Diego Alarcón taught the complete SolarTwins 2nd Summer School on "Solar Driven Water Desalination and Treatment Technologies" in the Department of Chemical Engineering in METU, Ankara (Turkey).

30th August - 1st September

Training

Diego Alarcon participated as lecturer in the second edition of the summer school "Solar water desalination and treatment technologies" held at the campus of the Middle East Technical University (METU) in Ankara (Turkey) within the framework of H2020 SolarTWINS (Solar Twining to Create Solar Research Twins) project.

11-15th September 2022

Technical exhibition

The Solar Treatment of Water Research Unit participated on the technical exhibition of PANIWATER Project technologies organized during the IWA World Water Congress & Exhibition. Copenhagen (Denmark).

12th September

Lecture

Participation of Guillermo Zaragoza as panellist with the talk “Integrating Renewables” in the Future of Desalination International Conference, organized by Saline Water Conversion Corporation and Global Water Intelligence in Riyadh (Saudi Arabia).

12-16th September 2022

Summer School

Partipation of PSA in 3rd SFERA-III/ 16th SOLLAB Doctoral Colloquium at ETH Zurich, Switzerland.

19th-21st September 2022

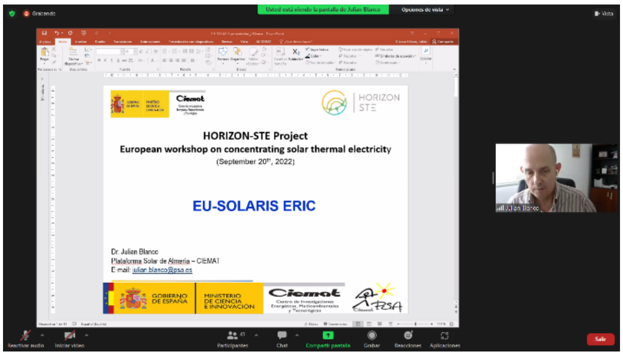
International school

Sixto Malato gave the lecture “Solar-based advanced oxidation processes: the long experience at the PSA” and Isabel Oller moderated and participated in the “Team working session on a specific case study: Almeria and Murcia (Spain): two areas one next to the other: water reuse or not reuse? This is the question”, in the International school on water reuse. Univ. Torino (Italy).

20th September

Workshop

J. Blanco and E. Zarza participated as speakers in the “HORIZON-STE European Workshop on CST Electricity” organized by CIEMAT and held on-line.



22nd September

Lecture

Guillermo Zaragoza gave an invited lecture “Desalination with solar energy” at the ETEIA Workshop on Energy Transition organized by University of Tás-os-Montes and Alto Douro in Vila Real (Portugal).

26th September 2023

Lecture

Lecture given by Esther Rojas entitled "Activities of the TES working group (2021)" at the Annual Meeting Task III - Solar Technology and Advanced Applications. International Energy Agency - SolarPACES organized prior to Solar Paces Conference 2022 in Albuquerque.

30th September

Dissemination Event

Participation of member of the Solar Thermal Application, Point-focus concentrating solar thermal technologies and Solar Treatment of Water Units in "The Night of European Scientists 2022" in Almería (Spain).

3rd - 7th October

Training

Guillermo Zaragoza and Diego Alarcón participated as lecturers in the Solar Desalination Course, held at the facilities of PSA in the context of project "Solar Desalination for Sustainable Brackish Water Management in Jordan for Agriculture and Drinking Water" coordinated by IHE Delft Foundation.

10th October 2023

Lecture

Lecture given by Esther Rojas entitled "Almacenamiento Térmico" in the Course "Tecnologías, Operación y Aplicaciones del Almacenamiento de Energía en Sistemas Eléctricos. Online course organized by SECARTYS & CIEMAT.

17th October

Interview

E. Zarza was interviewed at the PSA by the team of TVE for the TV program devoted to PSA within the series "Ciencia Maps" devoted to the Spanish ICTS.

20th October

Presentation

L. Valenzuela was an invited speaker at the 2nd Solar Energy Helix Event, Madrid (Spain). She made a presentation about "Recent Plataforma Solar de Almería (PSA) activities in collectors" development and testing: SOLTERMIN project".

25-27th October 2022

National conference

The Solar Treatment of Water Research Unit was part of the Organizing Committee of the XXI Reunión Científica de la Sociedad Española de Cromatografía y Técnicas Afines (SECyTA 2022) in Almería (Spain).

29th – 30th October

Meeting

A review meeting of HYDROSOL-Beyond project was held in Almería.

7-11th November 2022

Round Table

Participation of Sixto Malato as a Panelist in the Round Table entitled "Wastewater Reuse Towards a Circular Economy" at the 5th Iberoamerican Conference on Advanced Oxidation Technologies (CIPOA 2022), Cusco, Peru.

8th November

Workshop

Inauguration of the Living Lab Sustainable Desalination at PSA and co-creation event with its Community of Users.

9-11th November 2022

Workshop

Isabel Oller participated with the lecture "Tecnologías Solares para la obtención de agua en países con recursos limitados y zonas aisladas" in the "Jornadas Sobre el Valor del Agua" organized by the Academia de Ciencias Matemáticas, Físico-Químicas y Naturales de Granada, the University of Granada and Junta de Andalucía, in Granada (Spain).

15th November

Workshop

E. Zarza participated as invited speaker at the SUPEERA workshop held at the PSA. He made the presentation "Thermal storage integration into STE plants: a success story from Spain".

15th November 2023

Lecture

Lecture given by Rocío Bayón entitled "Thermal Storage for Electricity Production" at the SUPEERA Workshop with Joint Programs ES and CSP: Bringing research and industry closer: accelerating innovation and uptake of new technologies. Energy storage & Concentrated Solar Thermal Energy organized in Plataforma Solar de Almería.

22nd November

Lecture

Guillermo Zaragoza gave a keynote lecture "Improvements in membrane distillation towards brine concentration" at the Euromembrane conference in Sorrento (Italy).

28th November 2022

Workshop

Isabel Oller participated with the lecture "Fighting against water scarcity: (Solar) technologies integration for wastewater treatment and recovery at Plataforma Solar de Almería (Spain)" in the Solar Energy for the Water Industry Workshop organized virtually by the University of Melburne (Australia).

16 Publications

PhD Thesis

Thorsten Denk. Terrestrial Demonstrator for the Hydrogen Extraction of Oxygen from Lunar Regolith with Concentrated Solar Energy. (Tesis Doctoral Inédita). Universidad de Sevilla, Sevilla. Supervisors: Prof. Carlos Gómez Camacho https://hdl.handle.net/11441/133362

Ilaria Berruti. Assessment of novel Advanced Oxidation Processes for disinfection and decontamination of water. University Politechnique of Valencia, Spain. April 2022. Supervisor: Dra. M. I. Polo López.

Heidi Paola Díaz Hernández. (In Spanish) Caracterización energética de edificaciones en uso con técnicas de identificación de sistemas. Universidad Juárez Autónoma de Tabasco (UJAT). September 2022. Directors: Karla María Aguilar Castro (UJAT), María José Jiménez Taboada.

Line-focus Concentrating Solar Thermal Technologies Unit

SCI PUBLICATIONS

Behar O.; Valenzuela L.; Mohammedi K. Editorial: Advances in Solar Central Receiver Technology. **Frontiers in Energy Research**. 2022. 10. 909169. https://doi.org/10.3389/fenrg.2022.909169

Arias I.; Cardemil J.; Zarza E.; Valenzuela L.; Escobar R. Latest developments, assessments and research trends for next generation of concentrated solar power plants using liquid heat transfer fluids. **Renewable and Sustainable Energy Reviews**. 2022. 112844. 168. https://doi.org/10.1016/j.rser.2022.112844

Fernández-Reche J.; Valenzuela L.; Pulido-Iparraguirre D. Measuring Concentrated Solar Radiation Flux in a Linear Fresnel-Type Solar Collector. **Solar**. 2022. 2 (4). 401-413. https://doi.org/10.3390/solar2040024

Biencinto M.; González L.; Valenzuela L. Using time-windowed solar radiation profiles to assess the daily uncertainty of solar thermal electricity production forecasts. **Journal of Cleaner Production**. 2022. 379. 134821. 10.1016/j.jclepro.2022.134821

Chávez-Bermúdez I. A.: Rodríguez-Muñoz N. A.; Venegas-Reyes E.; Valenzuela L.; Ortega-Avila N. Thermal Performance Analysis of a Double-Pass Solar Air Collector: A CFD Approach. **Applied Sciences**. 2022. 12. 12199. https://doi.org/10.3390/app122312199

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Buendía-Martínez F.; Fernández-García A; Wette J.; Sutter F.; Valenzuela L. UV Degradation of Primary Mirrors in Outdoor Exposure and Accelerated Aging. **AIP Conference Proceedings.** 2022. 2445. 80001. https://doi.org/10.1063/50091462

Ahmend Chekh B.; Fernández-Reche J.; Valenzuela L.; Villasante C.; Kortaberria G.; Pulido-Iparraguirre D. Compact system for fast on-line geometry characterization of facets for solar concentrators. **AIP Conference Proceedings.** 2022. 2445. 70001. https://doi.org/10.1063/5.0086360

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Fernández-Reche F.; Pulido-Iparraguirre D; Valenzuela L. Medida de flujo de radiación solar concentrada en un captador solar lineal fresnel. **CIES 2022 ("XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar")** 20 - 22 June, 2022.

Alcalde-Morales S.; Valenzuela L.; Serrano-Aguilera J. J. Numerical Investigation of a Trapezoidal Cavity Multi-tube Receiver for a Linear Fresnel Collector. **XII National and III International Conference on Engineering Thermodynamics.** June 19th - July 1st, 2022

Alcalde-Morales S.; Valenzuela L.; Serrano-Aguilera J. J. Approach for modelling the thermal performance of a Linear Fresnel Collector with a Trapezoidal Cavity Multi-tube Receiver. **SolLAB 2022.** 12-16 September, 2022

López-Martín R.; Valenzuela L.; Amador-Cortés C. M. Device for Measuring Forces and Torques in Flexible Connection Joints for Parabolic Trough Collector. **28th SolarPaces Conference.** 27 - 30 September, 2022

Posters

Valenzuela L.; Pulido-Iparraguirre D.; Fernández-Reche F. Mejora en la eficiencia óptica de un captador lineal fresnel innovador. **CIES 2022 ("XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar")** 20 - 22 June, 2022.

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Valenzuela L.; López-Martín R.; Hernáiz J.; González J.; Arana J. Thermo-mechanical cycling results of the ROTAJOINT flexible interconnection installed in a parabolic trough test facility. **28th SolarPaces Conference.** 27 – 30 September, 2022

Point-Focus Solar Thermal Technologies Unit

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Campos L., Wilbert S., Carballo J., Meyer zu Köcker J., Wolfertstetter F., La Casa J., Borg E., Schmidt K., Zarzalejo L., Fernández-García A., Norde Santos F., García G. Autonomous measurement system for photovoltaic and radiometer soiling losses. ***Progress in Photovoltaics: Research and Applications.*** https://doi.org/10.1002/pip.3650.

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Chicos L.A., Zaharia S.M., Cempura G., Rodríguez J., Lancea C. Effect of concentrated solar energy on microstructure evolution of selective laser melted Ti-6Al-4V alloy. ***The International Journal of Advanced Manufacturing Technology.*** https://doi.org/10.1007/s00170-021-08136-6.

Alonso-Montesinos J., Monterreal R., Fernandez-Reche J., Ballestrin J., Lopez G., Polo J., Barbero F.J., Marzo A., Portillo C., Batlles F.J. Nowcasting System Based on Sky Camera Images to Predict the Solar Flux on the Receiver of a Concentrated Solar Plant. ***Remote sensing***. https://doi.org/10.3390/rs14071602.

Casanova M., Ballestrin J., Monterreal R., Fernandez-Reche J., Enrique R., Avila-Marin A. Improvements in the measurement of high solar irradiance on a 300 kWth volumetric receiver. ***Renewable Energy***. https://doi.org/10.1016/j.renene.2022.10.080.

Cruz N.C., Monterreal R., Redondo J.L., Fernandez-Reche J., Enrique R., Ortigosa P.M. Optical characterization of heliostat facets based on Computational Optimization. ***Solar Energy***. https://doi.org/10.1016/j.solener.2022.10.043.

Avila-Marin A.L., Fernandez-Reche J., Carballo J.A., Carra M.E., Gianella S., Ferrari L., Sanchez-Señoran D. CFD analysis of the performance impact of geometrical shape on volumetric absorbers in a standard cup. ***Renewable Energy***. https://doi.org/10.1016/j.renene.2022.10.032.

Carra E., Ballestrín J., Monterreal R., Enrique R., Polo J., Fernández-Reche J., Barbero J., Marzo A., Alonso-Montesinos J., López G., Díaz B. Interannual variation of measured atmospheric solar radiation extinction levels. ***Sustainable Energy Technologies and Assessments***. https://doi.org/10.1016/j.seta.2022.101991.

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Monterreal R., Enrique R., Barrera G., Fernández A., Rodriguez J. First Self-aligned Heliostat Prototype at the Plataforma Solar de Almería. *28th SolarPACES Conference* (Albuquerque, USA). 27-30/09/2022.

Zaversky F., Randez X., Baigorri J., Sánchez M., Avila-Marin A., Fernandez-Reche J., Füssel A. A cost-effective open volumetric air receiver design based on free floating stackable absorber modules. *28th SolarPACES Conference* (Albuquerque, USA). 27-30/09/2022.

Avila-Marin A., Morales A., Farchado M., San Vicente G., Carra M.E., Sanchez-Señoran D. Numerical Assessment of Enhanced Coatings in Wire Mesh Volumetric Absorbers. *28th SolarPACES Conference* (Albuquerque, USA). 27-30/09/2022.

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Cañadas I., Fernandez-Reche J., Rodríguez J., Ballestrín J., Morales A., San Vicente G., Galindo J., Candelario V. Accelerated Ageing Test Bench for Advanced Ceramic Slabs under Extreme and Controlled CSP Conditions. *EuroSun 2022*. 25-29/09/2022.

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Estremera-Pedriza N., Fernández-Reche J. Nueva instalación de longitud de onda selectiva para la caracterización y envejecimiento de materiales sometidos a altos flujos de radiación solar. *XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar* (Mallorca, Spain). 20-22/06/2022.

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Valenzuela L., Pulido-Iparraguirre D., Fernández-Reche J. Mejora en la eficiencia óptica de un captador Fresnel lineal innovador. ***XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar*** (Mallorca, Spain). 20-22/06/2022.

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Thermal Energy Storage for Concentrating Solar Thermal Technologies Unit

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E. Alonso, E. Rojas. Air solid packed-beds for high temperature thermal storage: practical recommendations for predicting their thermal behaviour. **Applied Thermal Engineering**. 2022. 202. 117835. https://doi.org/10.1016/j.applthermaleng.2021.117835

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Rodríguez M.; Rojas E.; Caruncho J.M. Thermal Storage Filler Material Distribution for the Polyphem Project. **AIP Conference Proceedings.** 2022. 2445. 160014. https://doi.org/10.1063/5.0085749

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Materials for Concentrating Solar Thermal Technologies Unit

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V.K. Thanda, Th. Fenda, D. Laaber, A. Lidor, H. von Storch, J.P. Säck, J. Hertel, J. Lampe, S. Menzd, G. Pieschee, S. Bergere, S. Lorentzou, A. Gonzales, A. Vidal, M. Roeb, Ch. Sattler. Experimental Investigation of the applicability of a 250 kW Ceria Receiver/Reactor for Solar Thermochemical Hydrogen Generation**. Renewable Energy**. Volume 198. October 2022. Pages 389-398. https://doi.org/10.1016/j.renene.2022.08.010

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Posters

Vidal A.; de la Calle A.; Jimenez S.; Coronado J. M.; Bayón A. SmartSolFuel: Smart Selection of Materials for Solar Fuel Production. **SolarPACES 2022.** 28-30 September 2022. Albuquerque (EEUU).

Solar Thermal Applications Unit

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I. Oller. Procesos de Oxidación Avanzada para la Regeneración de Aguas: eliminación de contaminantes de preocupación emergente e inactivación de patógenos. XXIII Curso de verano de la UAL. Guest lecture: Nuevas fuentes de agua: desalación y regeneración hacia la sostenibilidad del ciclo integral del agua. 14 Junio, 2022 (Almería).

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Sixto Malato. Plenary "Procesos avanzados de oxidación. Conceptos básicos, reactores y aplicaciones (aguas industriales y reutilización de efluentes urbanos)". V congreso colombiano de electroquímica (V CCEQ)" and "VIII seminario internacional de química aplicada para la Amazonia (VIII SEQUIAMAZ). 4-7 octubre 2022, Florencia-Caquetá, Colombia.

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