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PLATAFORMA SOLAR DE ALMERÍA

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ÍNDEX

1 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.

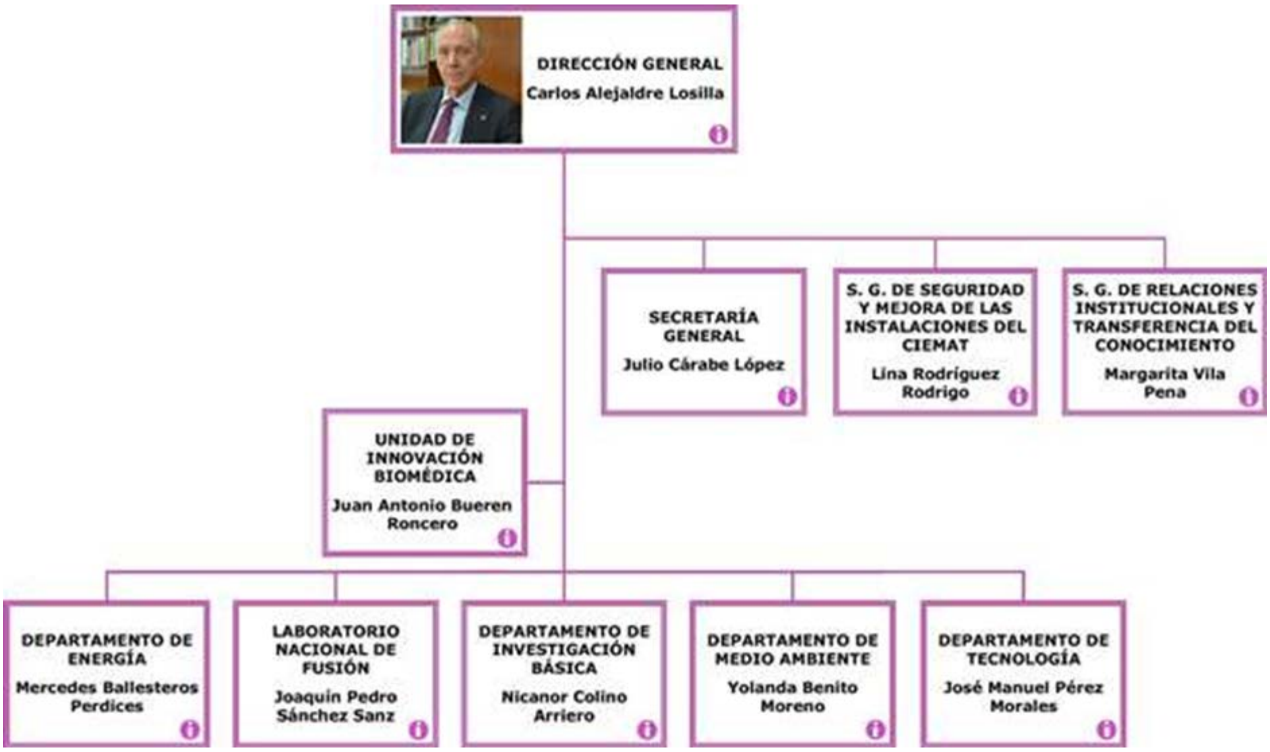


Figure 1. Integration of the PSA in the CIEMAT organization.

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:

- o Development of receivers for mean solar fluxes >1MW/m^2 and thermal efficiencies higher than 85% for temperatures above 600°C
- o New innovative working fluids with operating temperatures above 600°C for Rankine cycles, and above 750°C for unfired Brayton cycles.
- o Self-calibrating and cheaper heliostats, below 90 EUR/m^2 (installed).
- o High precision heliostat field and automated control for long focal distance and/or high temperature applications up to 1200°C.
- o Innovative plant configurations achieving better use of solar energy resource and technologies.
- o 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.
- o 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.
- o 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:
    - o Feasibility of materials for thermal storage systems
    - o Testing and characterization of prototypes, components and equipment for thermal storage systems
    - o Design and optimization of thermal storage systems following a holistic approach
    - o 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:
    - o 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.
    - o Development and standardization of suitable methodologies for the optical characterization and lifetime prediction of materials for CST technologies.
    - o Development and testing of cost-effective cleaning methods to reduce the water consumption in the O&M activities.
    - o 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).
    - o Development and testing of nanostructured materials to enhance thermal conductivity.
    - o 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 1000 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.

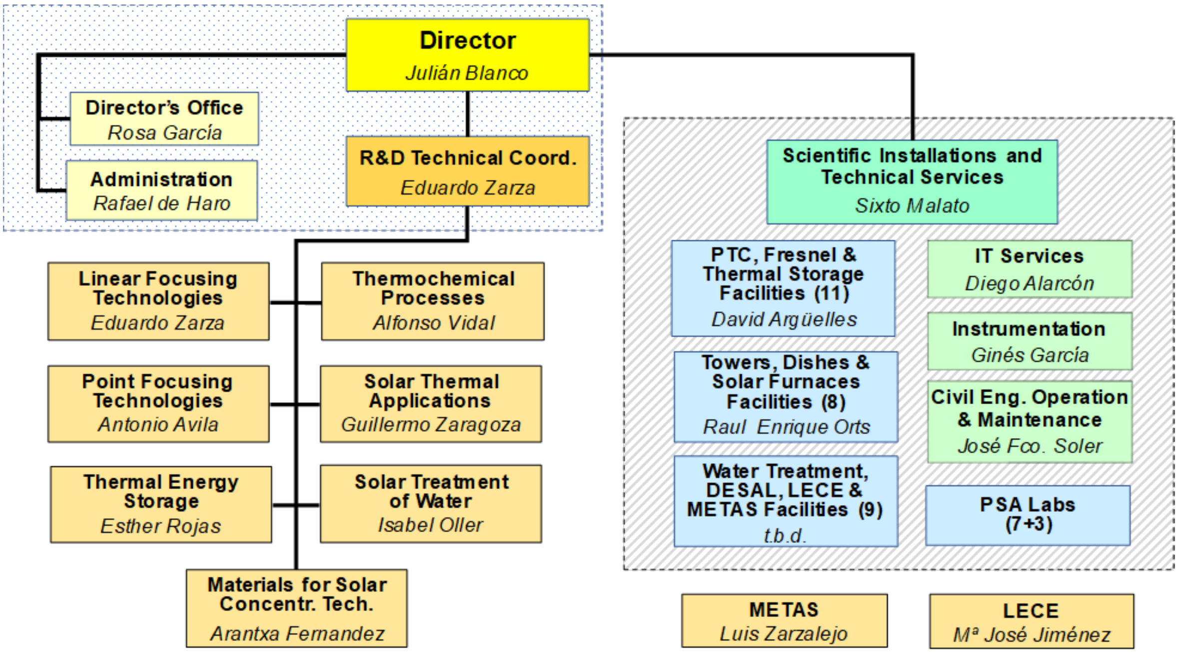


Figure 3. Internal organizational structure of PSA in 2021.

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 132 people that as of December 2021 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 122 people who work daily for the PSA, 68 are CIEMAT personnel, 13 of whom are located in the main offices in Madrid.

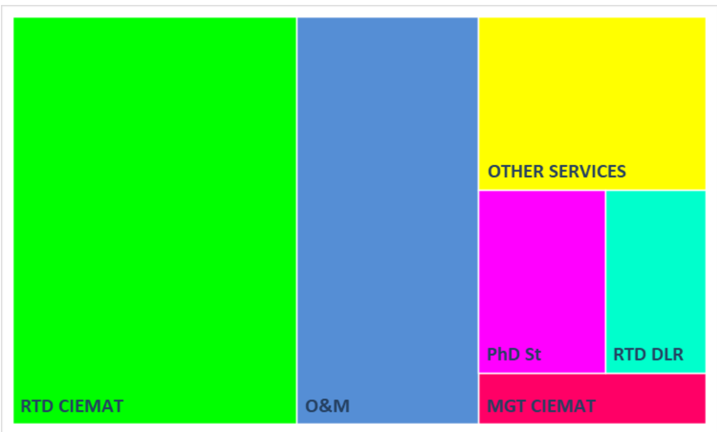


Figure 4. Distribution of permanent personnel at the PSA as of December 2021

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 32 people, 15 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 2021 totals 3.1M Euros (not including R&D personnel or new infrastructure).

Figure 5. PSA staff in 2021.

A number of relevant milestones have been achieved by EU-SOLARIS during past year 2021. A framework agreement has been signed in February 2021 between the Spanish Ministry of Science and Innovation (MSI) and CIEMAT to substantiate the support to and regulate the participation of Spain in EU-SOLARIS. Also, the consortium passed successfully a review hearing by the European Strategy Forum on Research Infrastructures (ESFRI) in April 2021. The objective of this project monitoring exercise is to check whether EU-SOLARIS reached the Implementation Phase as described in the Roadmap 2021 Guide. After this hearing, a new version of the ESFRI Roadmap has been issued by ESFRI on December 2021. In this updated version, EU-SOLARIS has been formally recognized as a 'Landmark' in the Energy domain (fully established research infrastructure which reached the Implementation Phase), leaving the former status of 'Project' (initiative under development).

2 Facilities and Infrastructure

Parabolic Trough Systems

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 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 6 and Figure 7) 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).

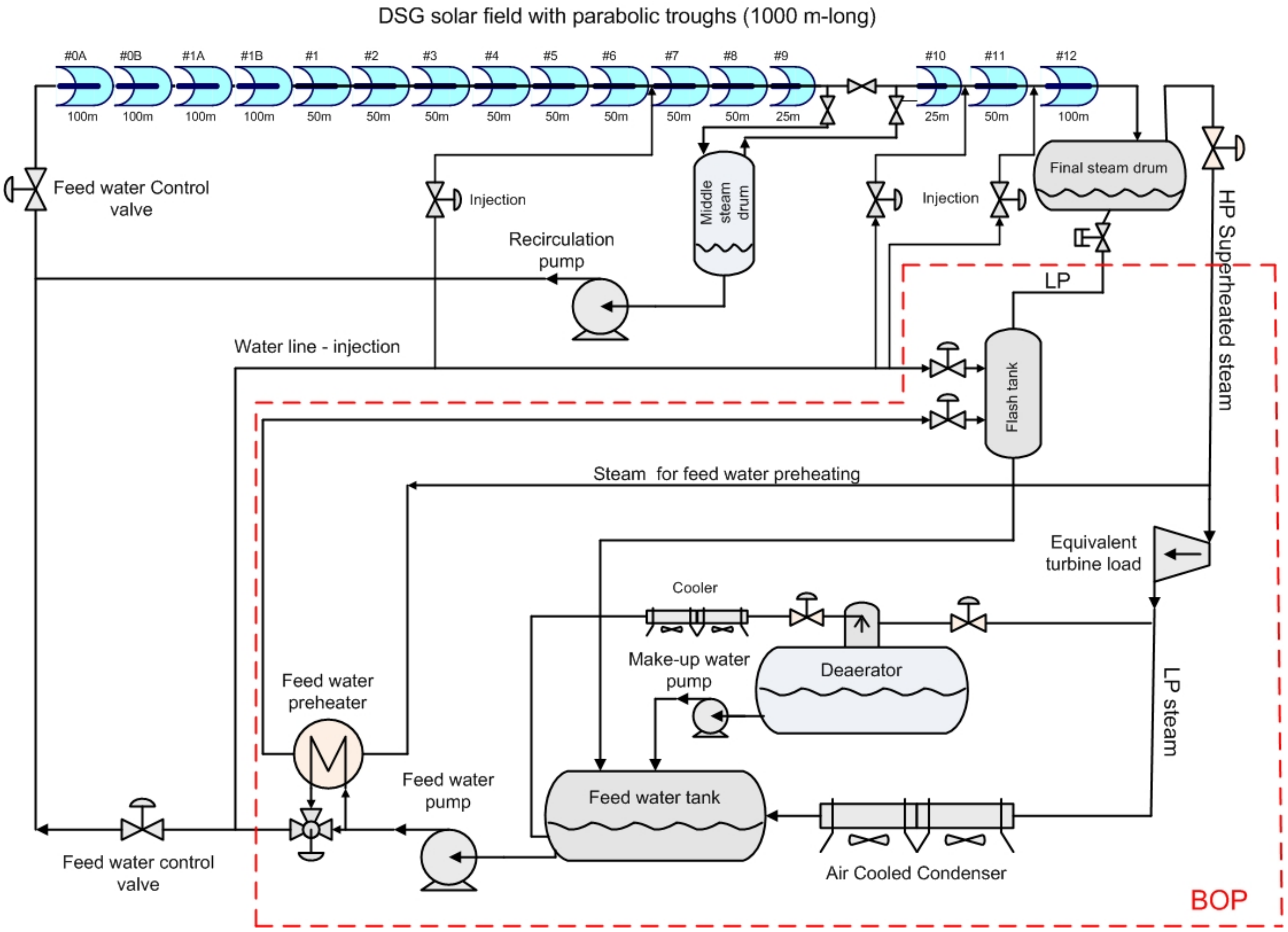


Figure 6. Simplified flow diagram of the PSA DISS loop.

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 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 7. 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.
- 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 it 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, being able to operate only one at a time (see simplified diagram of the facility in Figure 8). 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.

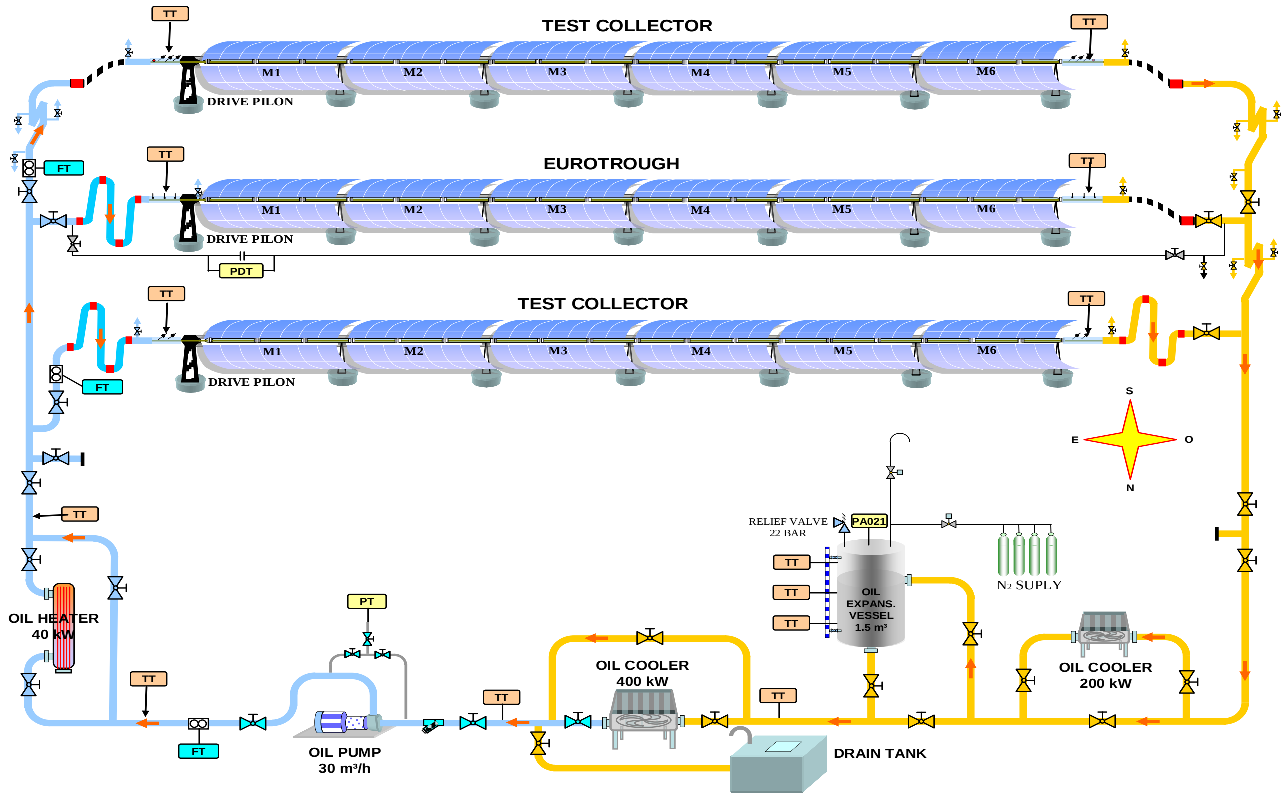


Figure 8. Diagram of the HTF test Loop located at the PSA.

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

- 1-m³-capacity oil expansion tank, with automatic nitrogen inertization.
- Oil circuit sump tank.
- 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.
- 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 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.

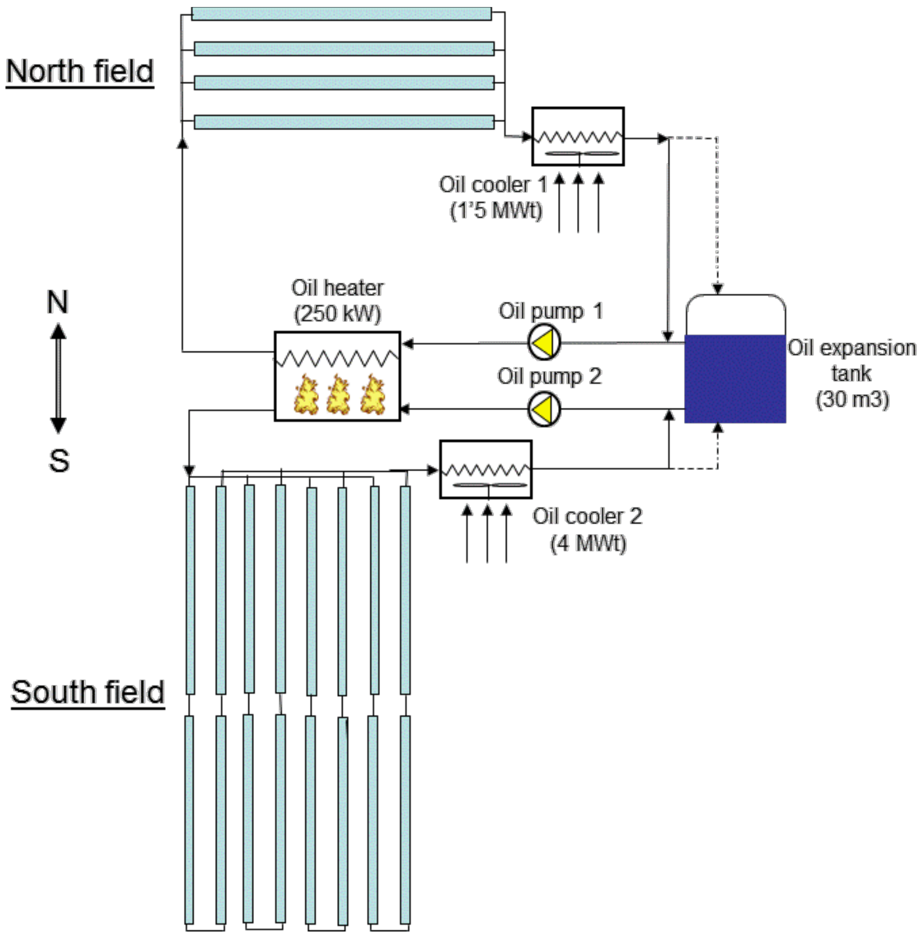


Figure 9. Simplified scheme of the PTTL facility

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, 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

An experimental closed loop is installed at the Northeast area of the PSA. It was designed and erected by the company *Iberdrola Ingeniería y Sistemas* in 2010 starting the test campaign along the following year. The pilot plant was transferred to CIEMAT to be used as testing loop.

The East-West oriented test loop 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 10. View of the PROMETEO test facility.

The collector modules are connected to the balance of plant (BOP) in parallel or in series configuration using the ad hoc set valve. 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 11. 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.

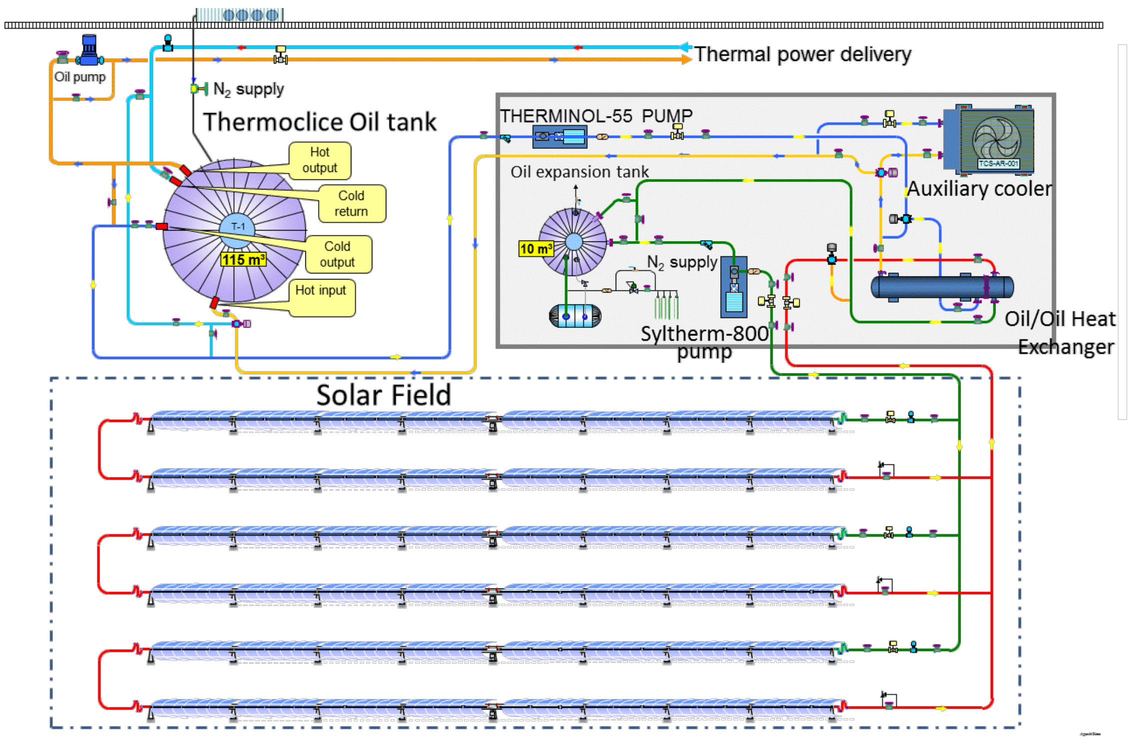


Figure 11. Diagram of the TCP-100 2.3 MWth parabolic-trough facility

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.

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 12) 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.

The IFL facility 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 12. 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.

The solar field is connected to a two-tank molten-salt thermal storage system to test their joint capacity for collecting and storing solar thermal energy with a view to making use of them in dispatchable high-performance thermal cycles.

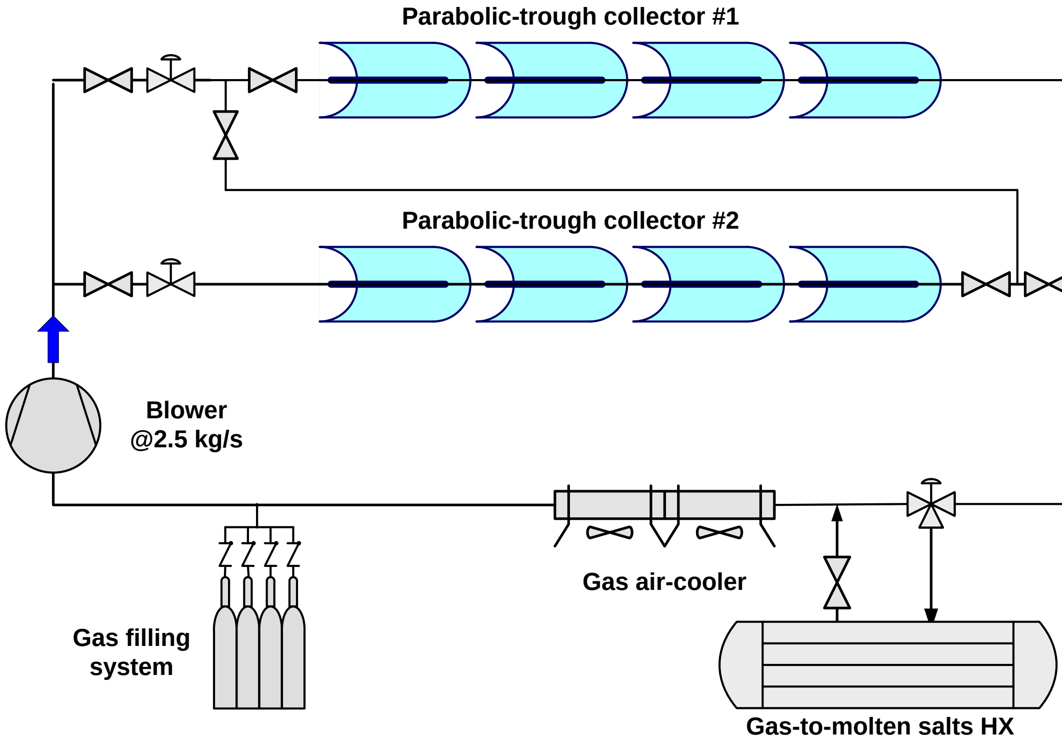


Figure 13. Simplified system diagram of the IFL experimental facility located at the PSA.

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 collector selected was the Polytrough 1200 prototype by 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.

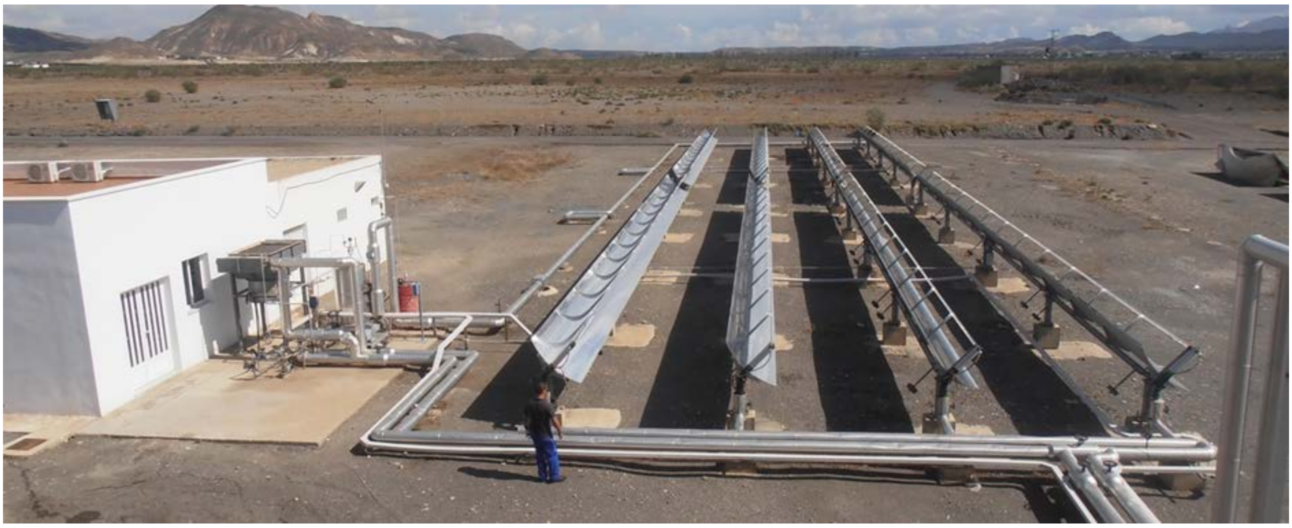


Figure 14. NEP PolyTrough 1200 solar field.

Installations associated with Parabolic Trough Systems

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 and 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 15. 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

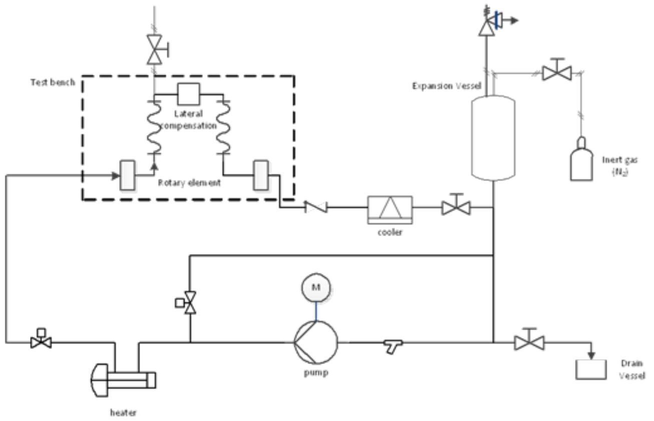
The REPA test facility is another test facility jointly implemented at PSA by CIEMAT and DLR. This facility is now used by CIEMAT and DLR in the framework of a joint collaboration.

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 Figure 16.a).

The balance of plant unit is composed of a variable speed HTF pump that circulates the HTF through a pipe with an adapted collar-type electrical heater 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 Figure 16.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 16. 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).

Central Receiver Systems

The PSA has two exceptional facilities for the testing and validation of central receiver 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 17) 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 17. 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 18)

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.

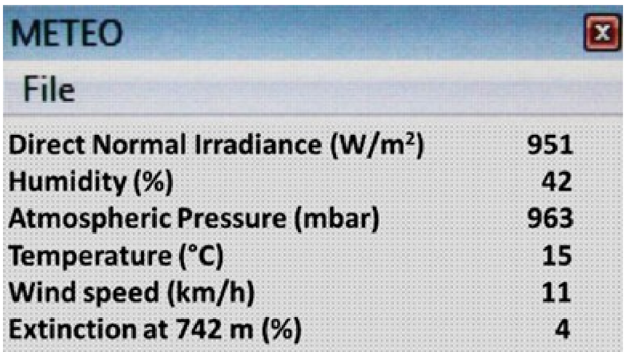


Figure 18. On-line measurement of the solar extinction in the control room of CESA-1 facility at PSA.

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 19. 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 20). 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 20. 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 21. 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 22) 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 22. View of a parabolic-dish DISTAL- II with the original Stirling engine.

Figure 23. 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 24), 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 24. 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 25 and Figure 26 show the heliostat installed in this solar furnace and a detail of the backside of the facet, respectively.

Figure 25. HT120 heliostat in tracking.

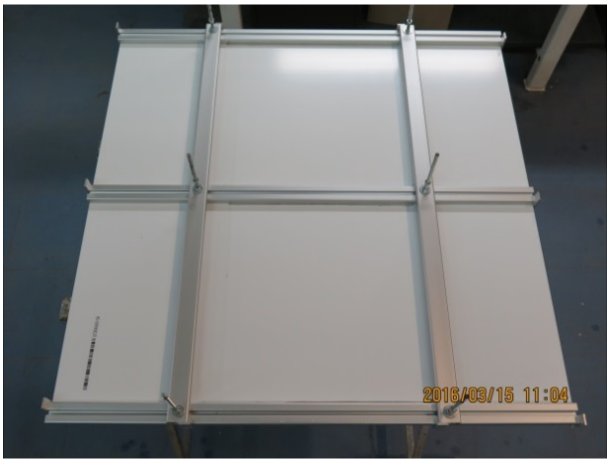


Figure 26. Back side of facet.

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.

The new parabolic concentrator, called FAHEX 100 (Figure 27), 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 28, 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.

Figure 27. Interior view of the PSA SF-60 Solar Furnace in operation.

Figure 28. Shutter of the PSA SF-60 Solar Furnace.

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 1000 W/m^2 are: peak flux, 670 W/cm^2, total power, 80 kW, and focal diameter, 22 cm.

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 29). 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 5000 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.

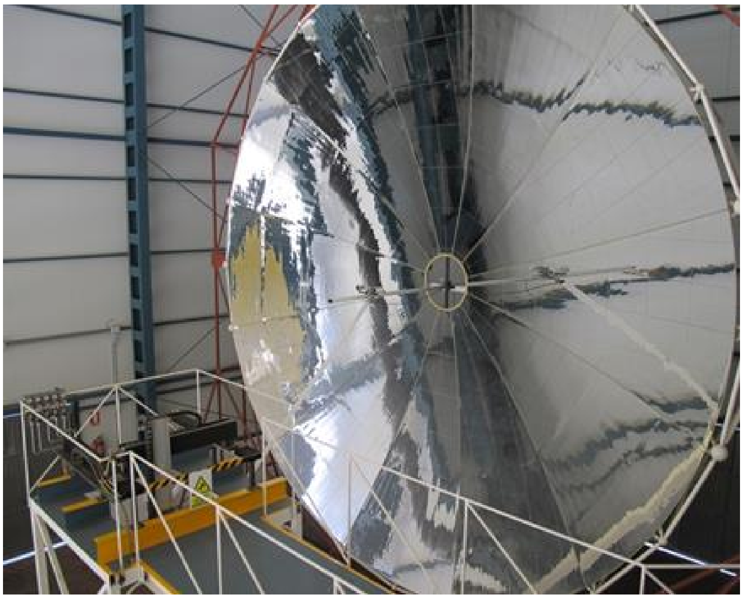


Figure 29. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

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 30. Concentrator of the SF-5 Furnace.

Thermal Storage Systems

MOSA: Molten Salt Test Loop for Thermal Energy Systems

This facility is composed of, on one hand, an outdoor test loop, which is a replica of a commercial thermal energy storage system with 40 t of nitrate molten salts and a two-tank configuration, and, on the other hand, an indoor test bench, named BES-II.

The outdoor loop of MOSA is the largest facility worldwide similar to a commercial two-tank molten salt storage system on a reduced scale, so everything related to this type of systems can be tested in this facility in a relevant and extrapolated scale. Some applications of this facility are:

- Checking of components (pumps, flowmeters, etc.) for their use in a liquid molten salt medium.
- Optimization of procedures in normal operation for a two-tank system configuration.
- Optimization of procedures in risk situations for a two-tank system configuration. Designing recovery procedures.
- Validation of models and simulation approaches for molten salt 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.

BES-II, an indoor installation at the PSA, is especially designed for the testing of valves, pressure transmitters and other small molten salts components under 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 31. Molten Salt (MOSA) outdoor test loop.

Figure 32. 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 900°C is possible. Thermocouples along its length and at different radial positions give an accurate map of temperature of the packed bed.

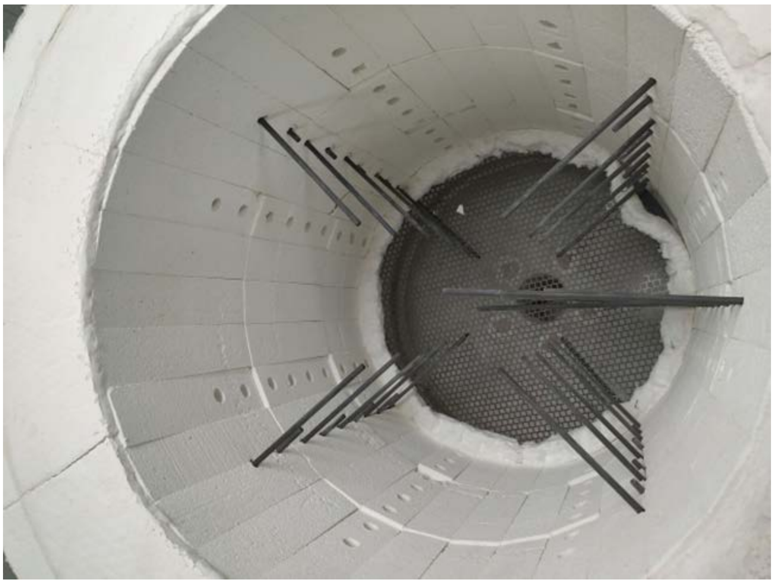


Figure 33. Picture taken from the top of the tank, showing its internal room and thermocouples at different lengths and radial positions.

Figure 34. 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)

(a) (c)

Figure 35. 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 (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. Each row has its own filling/emptying system consisting of two water deposits, from which the heat transfer fluid is pumped to the collectors at the beginning of the operation and where all the water volume in the collectors is spilt either at the end of the operation or when a temperature limit is reached (above 100°C). The solar field has flow control valves that allow having an equal distributed flow rate without further regulation. Besides, 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. 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.

Figure 36. 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 desalination system for testing purposes.

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)

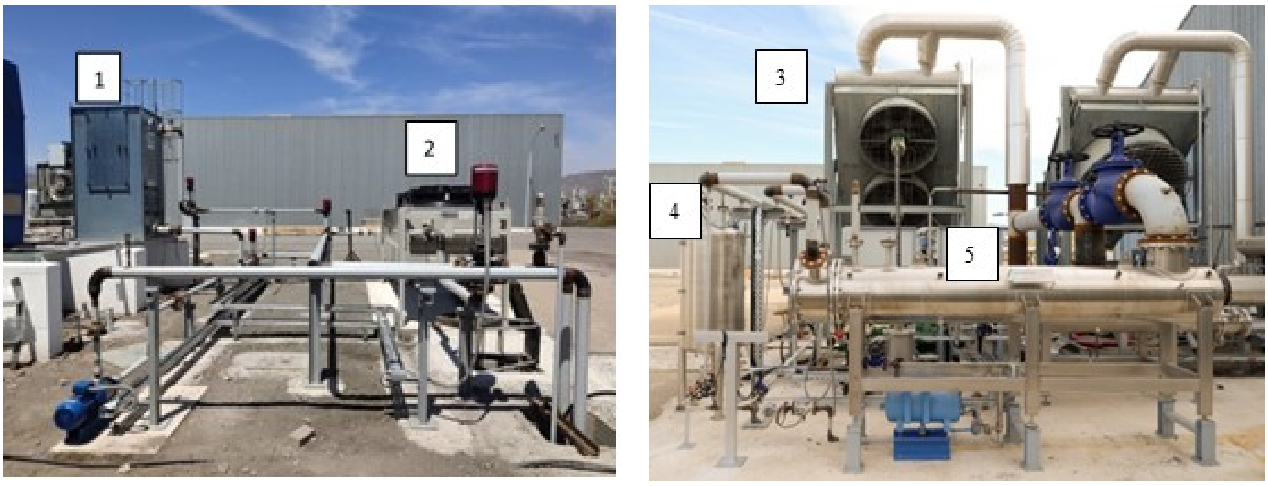
Figure 37. View of the outside of the CSP+D test bed building with the air coolers (a) and partial view of the interior of the CSP+D test bench (b).

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 38. 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:

1) Plate and frame airgap (AG) MD commercial modules from Scarab (total membrane area 2.8 m^2).
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).
3) Spiral-wound PGMD commercial modules Oryx 150 from Solar Spring (10 m^2).
4) Two spiral-wound AGMD modules from Aquastill with membrane areas of 7 m^2 and 24 m^2 each.

5) WTS-40A and WTS-40B units from Aquaver, based on multi-effect vacuum membrane distillation technology using modules fabricated by Memsys (5.76 m^2 and 6.4 m^2 total membrane area respectively).

6) 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 39. 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 (Figure 40) 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 41). 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 40. Test bed for FO-RO combination research.

Figure 41. 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.
- 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 42). 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 place on a platform titled 37° from the horizontal to maximize the global solar collection of photons through the year. In addition, the pilot plants are equipped with added systems for different purposes, for example: 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 supports that take up 90-95 L and can be colonized by active sludge from a MWWTP.

A 2 m^2 CPC collector (Figure 43) with 10 borosilicate glass tubes (50 mm diameter), illuminated volume of 22 L and a total volume of 75 L is connected to four electro 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 shape (CPC and U mirror type) has been installed at PSA (Figure 44). 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 which permits to increase water temperature prior to fill in the photo-reactors.

(a)

(b)

Figure 42. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II.

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	74/68.2	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.

Figure 43. View of 2 m^2-CPC coupled to Electro-Fenton pilot plant (ELECTROX).

Figure 44. View of new CPC and U-type photoreactors (NOVA 75 V 1.0).

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 wavelength limitation to 290 nm simulating external solar radiation. Temperature can be also modified and controlled in both systems by a cooling system (SUNCOOL).

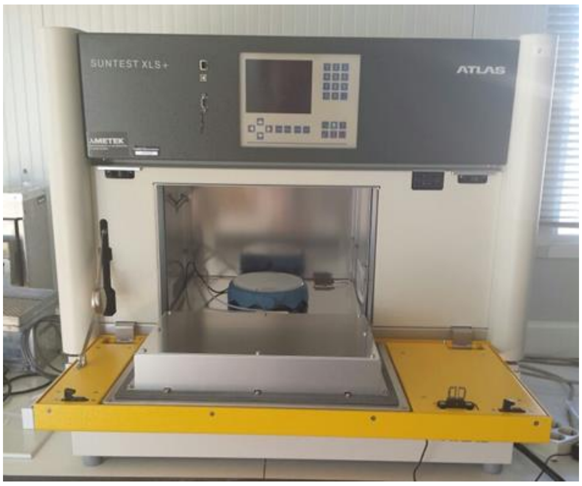


Figure 45. Solar simulator SUNTEST XLS+.

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 46.a).

(a)

(b)

Figure 46. (a) UVC pilot plant installed at PSA facilities and (b) recent improvements.

In 2021, the UVC pilot plant has been improved (Figure 46.b). 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) has been installed. The new module has been 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).

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 47):

- 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.
- 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 47. 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 48.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 48.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 48.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.

Figure 48. 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.

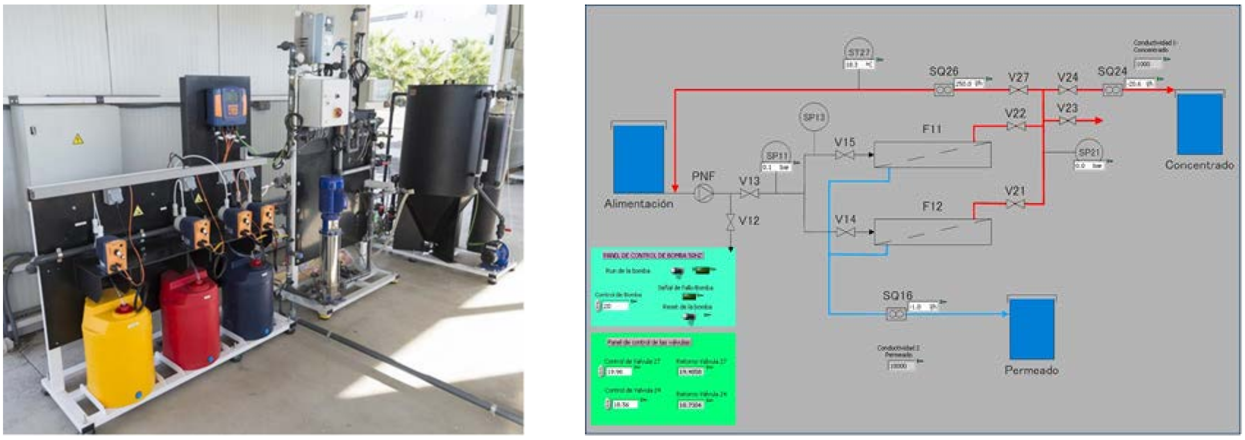
Solar CPC with direct injection of ozone

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 49. 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 50.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 50.b) for controlling the required quality of the permeate flow generated as well as the concentrated stream.



(a) (b)

Figure 50. 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 51). 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 51. (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 52). 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.

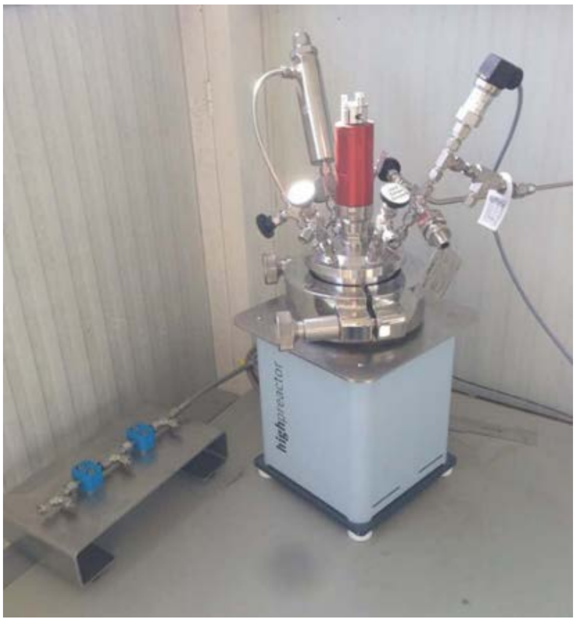


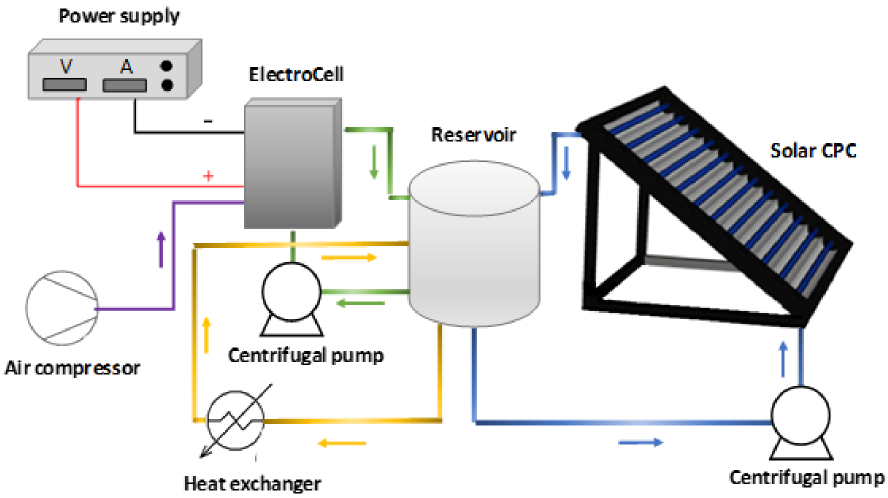
Figure 52. Wet Air Oxidation Pilot plant.

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 53).

(a)

(b)



(c)

Figure 53. 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 54), 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 54. 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 55) 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 55. 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 56).

Figure 56. 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 57). 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 has been 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 57. 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 58.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 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 58.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.

- 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 58.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 (2090°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.

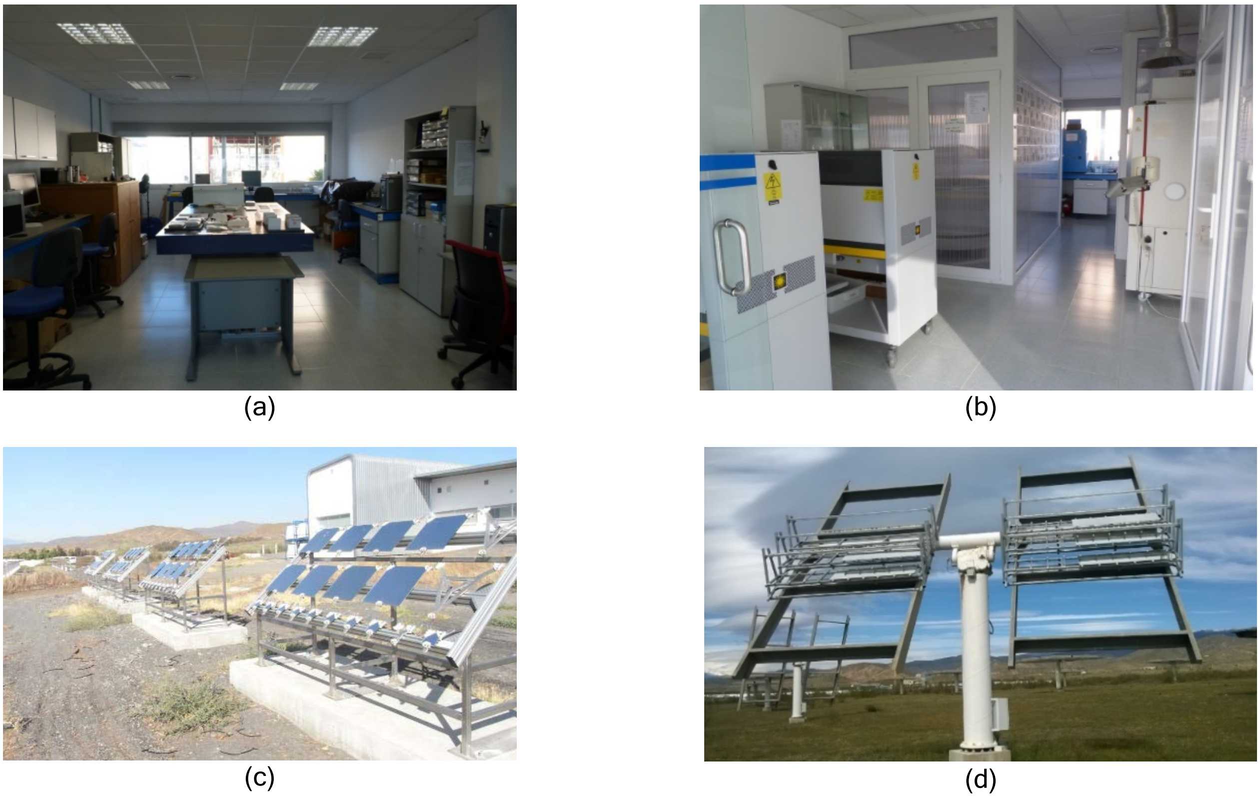


Figure 58. Optical characterization lab (a), durability analysis lab (b), outdoor test bench (c) and outdoor accelerated aging test bench (d) at OPAC facilities.

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:

1) 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.

2) 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.

3) CETeB Test cell: This is a new 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.

4) 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.

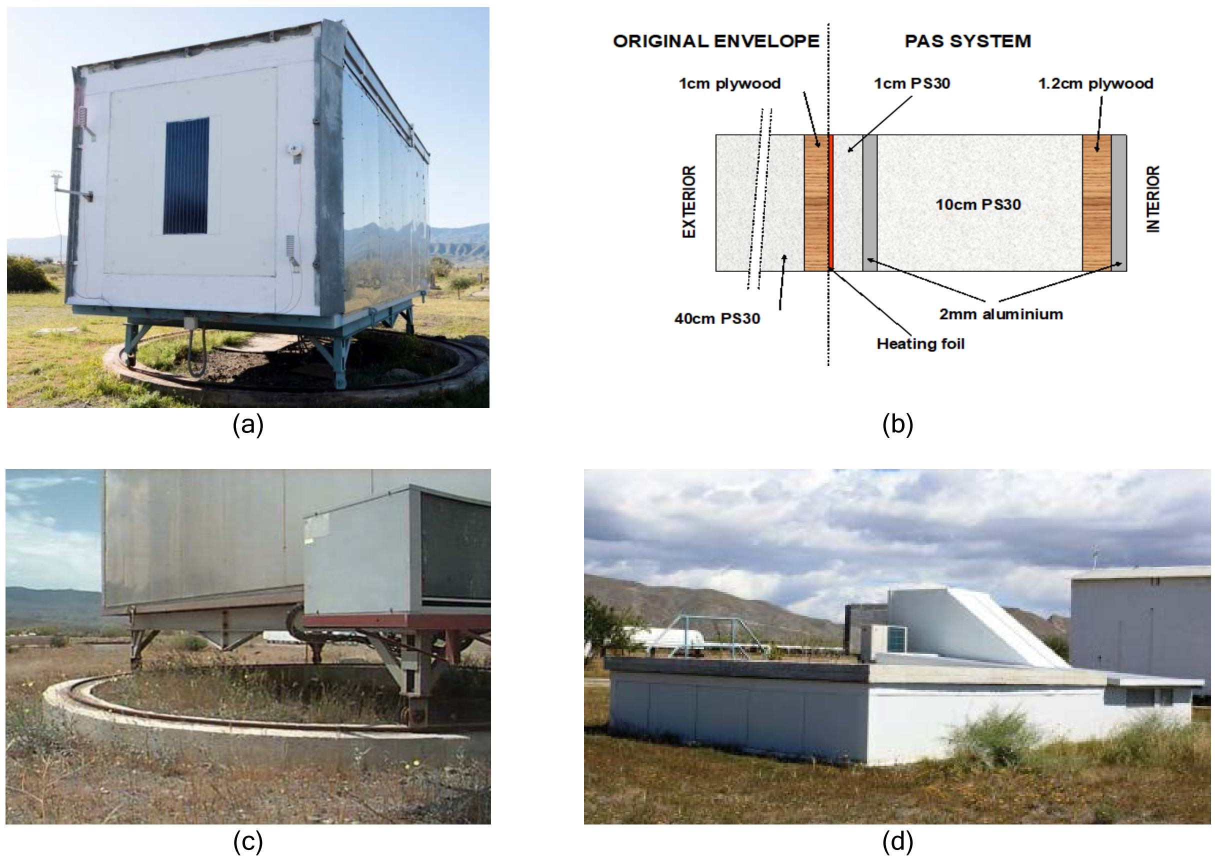
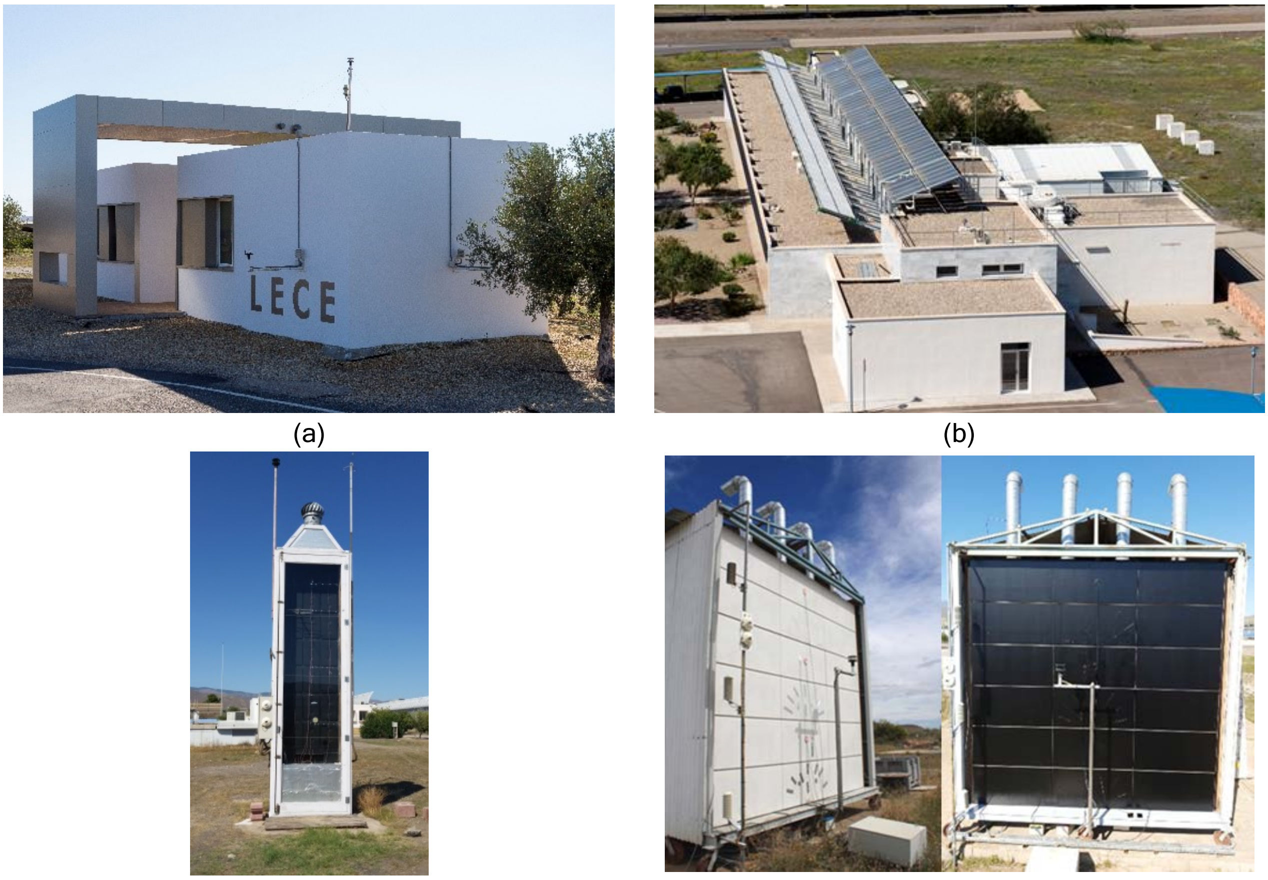


Figure 59. (a) CIEMAT's PASLINK test cell carrying out a thermal test of a PV module, (b) Schematic drawing of the PAS system, (c) Detail of the rotating device, (d) Exterior of the CETeB Test cell.

5) Single-zone building: This is a small 31.83 m2 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.

6) 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 m2 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.



(a) (b) (c) (d)

Figure 60. (a) Reference single-zone building, (b)ARFRISOL Building Prototype in use, (c) Solar Chimney. Configuration including Phase Change Material tiles, (d) Ventilated façade tested in a Test Cell. Different configurations with light and dark external face.

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.

3 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).

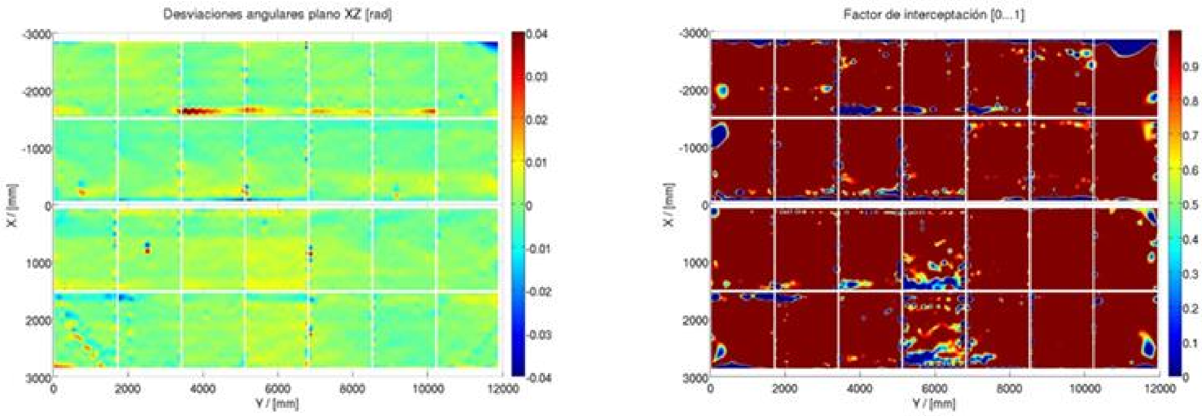
The equipment allocated to this activity at PSA is composed of:

- 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 61. 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 62. 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 1700°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 1000°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 63. 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 64. 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
- 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

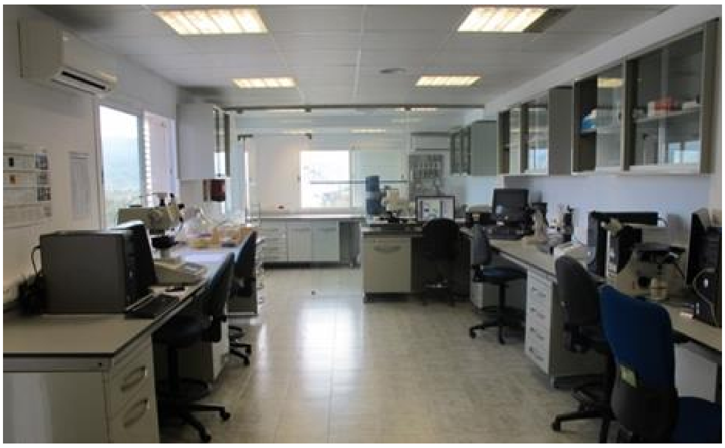
Thermogravimetry Room

The thermogravimetric Balance SETSYS Evolution18 TGA, DTA, DSC (temperature range from ambient to 1750°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 1750°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 1000°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 65. View of a) the Microscopy Room, and b) the thermogravimetric balance inside of its Room.

Thermal Cycling Room

It includes the instrumentation necessary for thermal cycling:

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

Electronic microscope Room

The indoor devices located in the four rooms described above are complemented by an electronic microscope installed in its own room, which is shared by the Solar Treatment of Water Unit and the Solar Concentrating System units. For further details see section 0.

Receivers testing and characterization for concentrating solar thermal systems - SRTLab

This activity line comprises both linear tube-type receivers and volumetric air receivers.

HEATREC and RESOL

There are two test benches at PSA for the testing of linear receivers: a) a test bench called HEATREC (see Figure 66.a), for measuring heat loss of single receiver tubes under indoor laboratory conditions, and b) an outdoor test bench called RESOL (see Figure 66.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.

(a) (b)

Figure 66. 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.

HEATREC device allows to characterize heat losses of receiver tubes with inner diameter greater than 62 mm and tube length lower than 4.5 m. Measurements can be performed for absorber 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.

Besides HEATREC and RESOL, the activity line devoted to linear receivers is 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 evaluate 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 devoted to testing and characterization of solar reflectors.

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

- Perkin Elmer LAMBDA 950 Spectrophotometer (Figure 67.a).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrated sphere manufactured by Pike (Figure 67.b).
- LEICA DM4 M optical microscopy with image acquisition system and software for image analysis (Figure 67.c).
- KSV CAM200 goniometer for measuring contact angles (Figure 67.d).
- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (Figure 67.e).
- BROOKFIELD LVDV-I+ Viscometer.
- BRUKER DektakXT stylus profilometer with optical camera and software for surface analysis (Figure 67.f).
- TABER linear abrader model 5750, equipped with different types of abrasive materials to measure the abrasion resistance of coatings and materials (Figure 67.g).
- 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 67.h.)
- 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 kiln with a maximal temperature of 1200°C.

- Controlled atmosphere kiln with a maximal temperature of 800°C.
- 500x400x600 mm forced convection kiln with a maximal temperature of 550°C.

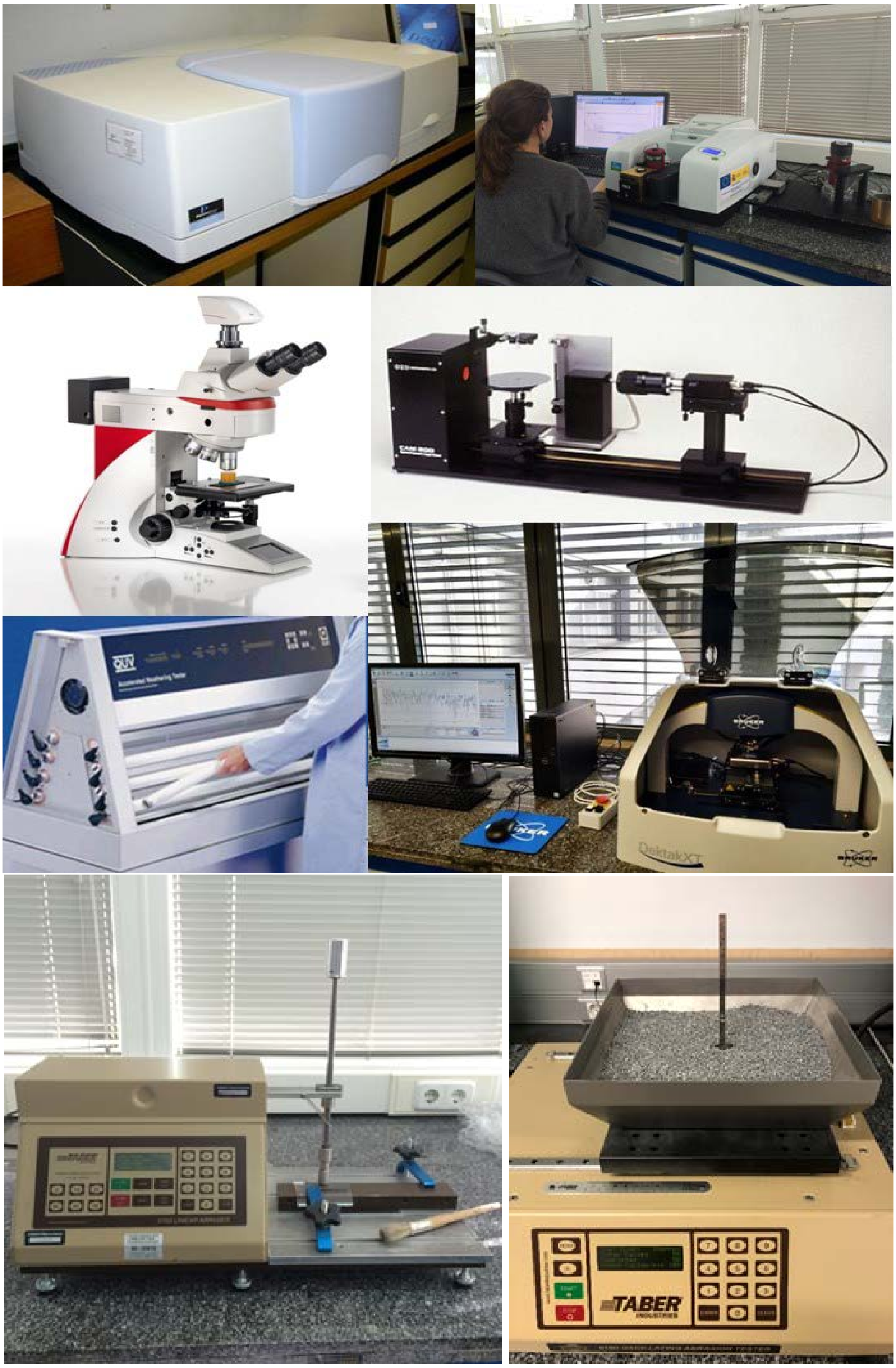


Figure 67. Advanced optical coatings laboratories equipment.

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 68) 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.

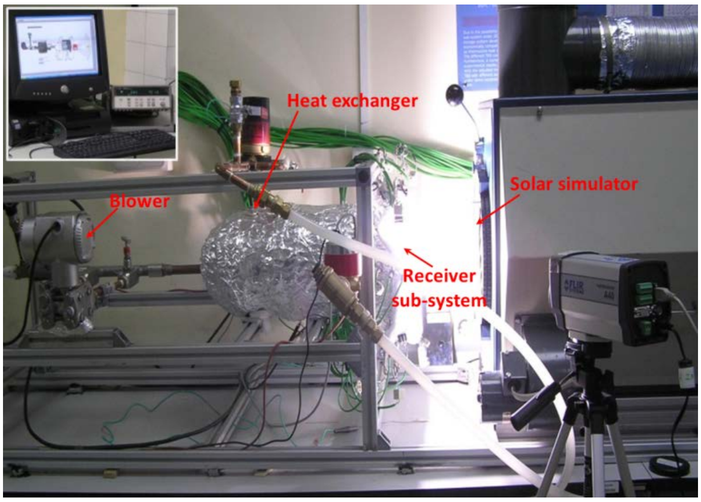


Figure 68. Test bench for volumetric receiver testing.

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

3) Laboratory for the Assessment of Thermal Storage Materials - TESLab

This laboratory is intended to study the feasibility of materials as storage media at a preindustrial scale. Focussing on the performance of phase change materials (PCM) for latent storage the following instruments are available:

- HDR: Small furnace under ambient air atmosphere with an accurate control of heating/cooling rates, sample temperature monitoring; allows PCM melting/freezing cycles up to 500°C and subsequent cycles, or cycles with stand-by periods. Sample size: 10-20 g.
- SUBMA: Small closed device inside a furnace, for 30-40 g sample sizes. It allows tests under inert atmosphere (N_2, Ar), controlling furnace temperature and gas flow, sample temperature monitoring. PCM melting/freezing cycles up to 500°C, subsequent cycles as well as cycles with stand-by periods can be performed.
- AgH: Furnace under ambient air atmosphere and with an accurate control of heating and cooling. It allows PCM melting/freezing cycles up to 350°C, subsequent cycles, and cycles with stand-by periods for 10-20 g sample sizes.

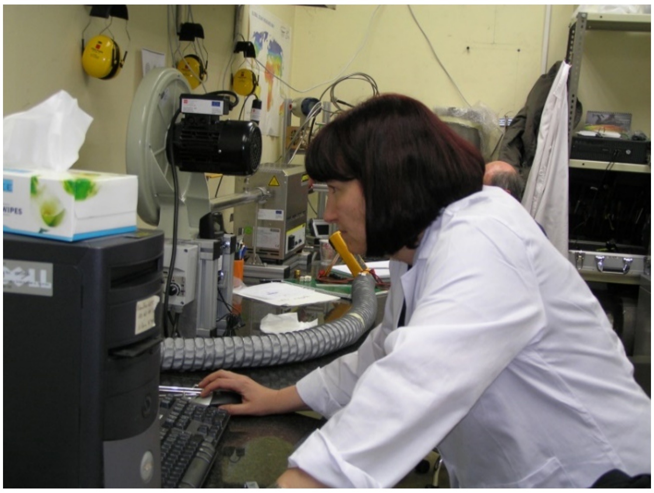


Figure 70. Working using the HDR device

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 testbed **Error! Reference source not found.**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 71. 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 72) 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 72. 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 73). 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 73. 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 74). It is equipped with four large work benches, two gas extraction hoods, two heaters, a kiln, ultrasonic bath, three centrifuges, two UV/visible spectrometers, a fluorometer, 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 74. General view of the new PSA Water Technologies Lab.

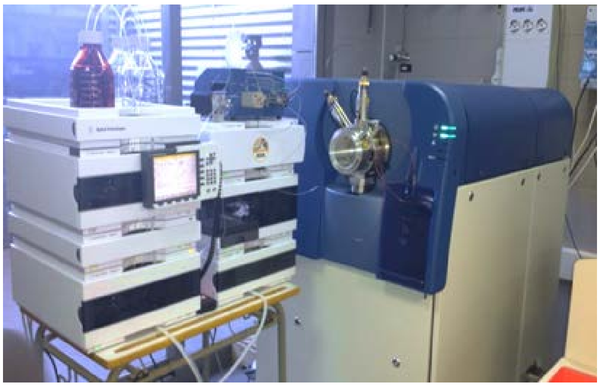
Chromatography laboratory

This laboratory (Figure 75.b) is equipped with three high performance liquid chromatographs with diode array detector (HPLC-DAD and two UPLC-DAD) with quaternary pumps and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which allows working with low concentration of pollutants (Figure 75.c) and two ion chromatographs (Figure 75.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 75.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) has been acquired (Figure 73 e). This equipment consists of a binary pump for working in constant flow or constant pressure modes, column oven (thermostated from 10 to 80ºC), 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 75. 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 76) 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.

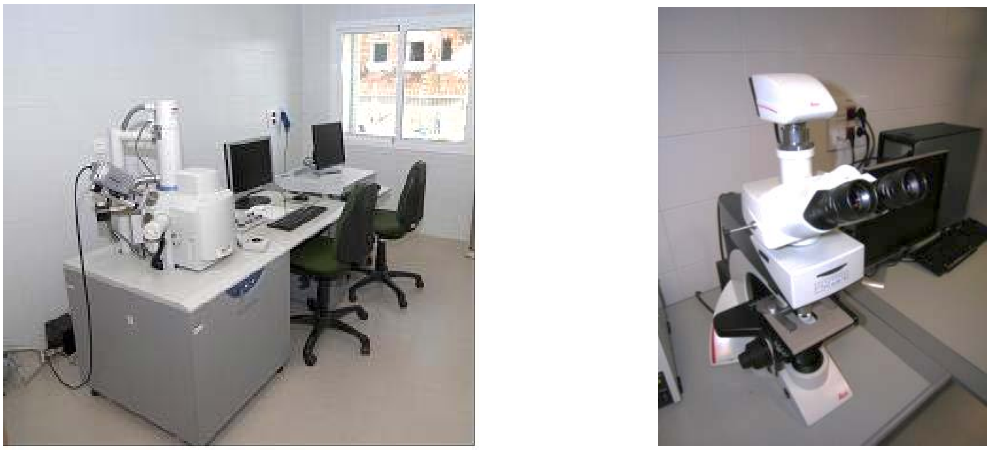
Figure 76. General view of the microbiology lab at PSA facilities.

This lab is also equipped with ultra-fast real-time quantitative PCR (Polymerase Chain Reaction) equipment, fluorospectrometer and spectrophotometer NanoDrop 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 storage in a reproducible way without any risk of cross contamination between samples.

Microscopy laboratory

The microscopy laboratory is a 11 m^2 room (Figure 77.a) in which a Scanning Electron Microscope (SEM) is installed. Besides, the microscopy laboratory also has environmental secondary electron detector (ESED). For the preparation of microbiological samples and catalysts to be analysed in the SEM, the system is complemented with a metal coater and critical point dryer. In this room it is also located two optical microscopes: i) a fluorescence and phase contrast combination optical microscope and, ii) a FISH microscope (Leyca) with 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 of key microorganisms within a heterogeneous population (Figure 77.b).

In addition, the system is completed by a station for photographic documentation, consisted in 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.



(a) (b)

Figure 77. a) SEM (Scanning Electron Microscope). b) 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 78).

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 m
- Vertical temperature and humidity profile at 2 and 10 m
- Miscellaneous weather information: rain gauge, barometer and psychrometer

Figure 78. 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 pyreheliometers (absolute cavity radiometer PMOD PMO6-CC) and a total of 19 field pyreheliometers 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 79). These facilities are operated in collaboration with the Instrumentation Unit.

Figure 79. Calibration facilities.

Since the beginning of 2018 there are seven new radiometric stations fully operational all around the PSA area. 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 80. PSA radiometric stations.

4 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).

In spite of the Covid pandemic, which had an obvious impact on the PSA activities in 2021, a great effort was also devoted to dissemination activities, through virtual participation 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 development, testing, and evaluation of components for line-focus solar collectors (SOLTERMIN project and bilateral contracts with Spanish companies), development of new techniques and measurement capabilities (SFERA-III project), testing of a new silicone fluid for parabolic troughs (SING and Si-CO projects), modelling and simulation of power plants with parabolic-troughs for analysis of 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 related to operation and maintenance of existing solar power plants continued within the framework of partnership agreements or technical services in 2021.

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 a Guideline, Si-HTF Guideline
- 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

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).

5 Point-Focus Solar Thermal Technologies Unit

Introduction

The main lines of research have been focused on: 1) the straight commitment to volumetric receiver technology, 2) the development, testing and evaluation of new heliostat concepts and designs, and 3) the improvement in the measurement of variables of control in real time for power tower plants, such as high solar irradiance and solar extinction. Within the European project NEXTOWER, officially finished in June 2021, an extensive experimental campaign of a new volumetric receiver design with a linear cell size variation produced by the Voronoi tessellation technique and tested at CESA-1 tower was performed. Moreover, within the SOLTERMIN project, two main tasks were performed: i) The optical and thermal evaluation of quartz windows with anti-reflective treatment for their application in volumetric receivers, in collaboration with Materials for Concentrating Solar Thermal Technologies Unit, and ii) The structural analysis of a new heliostat concept, in collaboration with Materials of Energy Interest Division. At the same time, due to the Unit's wide experience on heliostats design and testing, the assessment of different heliostat prototypes of different companies (Solarblue, ATH146) was performed. The AdaptedHelio project started with the installation of different sensors on the solar field of CESA-1 facility. Finally, the Unit is clearly focused 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, during 2021, the first commercial atmospheric extinction measurement system developed at CIEMAT 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). Moreover, our predoctoral researcher Marina Casanova Molina presented her PhD Thesis "Measurement of high solar irradiance in central receiver plants" placing PSA in the race to obtain a system that is applicable to commercial plants.

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
- Soluciones termosolares para integración en procesos industriales, SOLTERMIN
- Wind adapted heliostat, based on field measurements in the heliostat field and validation of wind tunnel measurements, AdaptedHelio
- PV plant with thermal cogeneration, SOLARBLUE
- Solar extinction measurement system commercialization - Ref. 8510/2018
- ATH146 heliostat prototypes

6 Thermal Energy Storage for Concentrating Solar Thermal Technologies Unit

Introduction

During 2021, researchers of this Unit have been actively working in international, national and regional funded projects, listed in the following paragraph. 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.

Through its experts, the Thermal Energy Storage Unit participates actively 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 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 loops (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 in real solar conditions.
- Modelling the behaviour of TESS, with own and commercial programs.
- Optimizing the operation strategies of TESS in order to obtain a maximum advantage of the stored energy.

List of funded projects the unit has been involved in

- 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 81. Researchers of Thermal Energy Storage Unit in 2021

7 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 2021 we have worked on the development and testing of selective and non-selective absorbers (NEXTOWER and SOLTERMIN 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), testing of solar reflectors under several outdoor environments as well as accelerated aging conditions (SOLTERMIN and SOLARTWINS projects), accelerated aging of materials for CST technologies under high radiation fluxes in solar furnaces (NEXTOWER, SFERA-III, SOLTERMIN, HiPIMSOLAR and HIDROFERR projects) 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 two 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.

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

(a)

(b)

Figure 82. Unit Staff a) at CIEMAT Headquarters in Madrid and b) at Plataforma Solar de Almería in Tabernas (Almería)

8 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 2021, 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

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

9 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).
- Electricity generation through saline gradient processes regenerated with thermal solar energy: reverse electrodialysis (RED) and pressure retarded osmosis (PRO).
- 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.

During 2021, the Unit has continued its relevant R&D activities within the framework of national and international projects. Remote work has practically mitigated the effects of the pandemic and even all the installations can be operated remotely. Most notable is the participation in H2020 projects with a strong participation in the industry sector: WATER MINING, EERES4WATER and INTELWATT. In particular, the first one implies the creation of a Living Lab at PSA, involving a Community of Practice on solar desalination with zero liquid discharge and the production of high-quality salts and water suitable for agriculture. Two new PhDs have started in 2021, one devoted to the application of solar-powered MD for brine concentration and another to the development of advanced control techniques for solar desalination.

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.

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
- 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, SOLARTWIN

Figure 83. Solar Thermal Applications Unit staff in 2021.

10 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 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 2021 edition has maintained the online mode within a series of specific webinars (>70 on-line attendants) and co-organised by the Solar Treatment of Water Unit.

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 "S*olar 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) and NAVIA projects and AQUALITY Marie Skłodowska-Curie Action.
- Solar photochemical processes for the remediation of industrial wastewaters, related with CALYPSOL project and ELECTRONÍQUEL service contract.
- Integration of Advanced Oxidation Processes with other water treatment technologies (NF/UF; Ozone, Bioprocesses, etc.), related with AQUALITY Marie Skłodowska-Curie Action and CALYPSOL project.

- Evaluating photocatalytic efficiency of new materials under solar light in pilot reactors, related with CALYPSOL and NAVIA projects.
- Photocatalytic and photochemical processes for water disinfection in different scenarios related with ENERGICA project and SolarDew prototype testing (Green Deal).
- Pilot solar photo-reactors for production of hydrogen and other photo-fuels, related with SolarFuture project.

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
- Operation of two single layer panels prototype from SolarDew at the Plataforma Solar de Almeria
- Revalorization of acids and heavy metals in waste streams from surface treatments with membrane technologies

Figure 84. Solar Treatment of Water Unit staff in 2021.

11 Projects

Standardization activities at Spanish and international level, Technical Committees *IEC/TC117* and *AEN/CT206-SC117*

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

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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.

Objectives: The scope of the international committee IEC/TC-117 implemented within the umbrella of the International Electrotechnical Commission, and the sub-committee AEN/CTN-206-SC117 implemented within the Spanish AENOR standardization body is the development of standards for the Solar Thermal Electricity (STE) sector by putting together the experience of R+D centres, Industries, Engineering companies, components manufacturers and promoters.

Achievements in 2021: 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 2021. This contribution has been made under the umbrella of the international standardization committee IEC/TC-117 and the Spanish AENOR sub-committee AEN/CTN206/SC117.

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 participated in the working group related to a new standard for "*Sistemas de almacenamiento térmico directo*".

At an international level, the LFCST technologies unit has undertaken the Secretariat of the technical committee IEC/TC-117 in 2021 and it 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*
- 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*.

- IEC TS 62862-2-1:2021 “Solar thermal electric plants - Part 2-1: Thermal energy storage systems - Characterization of active, sensible systems for direct and indirect configurations” ((publication date: 2021-02-04).
- 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 62862-3-1 “Solar thermal electric plants – Part 3-1: G*eneral requirements for the design of parabolic trough solar thermal electric plants”*
- PT 62862-3-5 “Solar thermal electric plants – Part 3-5: *Laboratory reflectance measurement of concentrating solar thermal reflectors*”
- PT 62862-3-5 “Solar thermal electric plants – Part 3-6: *Accelerated Aging Tests of Silvered-Glass Reflectors for Concentrating Solar Technologies*” PT 62862-4-1 “Solar thermal electric plants – Part 4-1: *General requirements for the design of solar tower plants*.
- PT 62862-5-2 ED1 *General requirements and test methods for large-size linear Fresnel collectors*, which will be 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: Coordination and support action to provide support to the realisation of the Implementation Plans of the SET-Plan for CSP. The project proposes solutions and pathways for overcoming 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. These projects were integrated into the Implementation Plan (IP) of SET-Plan.

Objectives: Assessment of the conditions required for replicating in European countries the commercial cost levels (< 10€ cents/kWh) that already 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 2021: PSA has mainly contributed to work packages (WP) 2 and 3 of HORIZON-STE in 2021. Within WP2, PSA activities have been mainly focussed on the preparation of the information concerning the R&D sector in Portugal, Greece and Spain. This information is to be included in the relevant country reports under preparation by ESTELA. PSA collected information from Internet, local R&D entities and other documents available, thus preparing a report about the situation of the R&D sectors in these three countries (i.e., funding sources for R&D projects, R&D entities, R&D projects underway and the partners involved, and research infrastructures available). Concerning the

R&D projects developed in these countries and the local partners involved, the information delivered by the Joint Programme CSP of EERA was analysed.

In WP3, PSA has been very active in the preparation of the updated Implementation Plan (IP) for CSP, working in close collaboration with the Implementation Working Group (IWG), which is coordinated by Spain, and other R+D Spanish entities. A complete draft for the new IP was almost ready for final comments.

Finally, PSA has collaborated with the other partners of HORIZON-STE in the elaboration of the project proposal "Support to the Activities of the Concentrated Solar Thermal Technology Area of the SET Plan, CST4ALL", submitted to the H-EUROPE call HORIZON-CL5-2021-D3-02-15.

Solar Twining to Create Solar Research Twins, SolarTwins

Participants: METU, CIEMAT, DLR

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

Background: Concentrating Solar Thermal (CST) Technologies offer promising solutions to many societal challenges that lead to a sustainable and low-carbon energy future. Currently, Europe is a global leader in CST technologies, but this leading position is increasingly being challenged by large investments by 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 with a duration of 3 years.

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 (ESRs); 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 2021: Three ESR (Early Stage Researchers) from METU involved in the Joint Research Lines between METU and PSA related to Solar Treatment of Water and Desalination spent at PSA the last week in September to visit our facilities devoted to these topics and meet PSA researchers who are working in these activities. The ESRs from METU were informed about the technical features of the PSA facilities and how they are currently used in R+D activities. Additionally, two of those ESRs extended their stay at PSA until October 8th to participate in the Summer School organized by PSA within the framework of the project SFERA-III.

Concerning Solar Treatment of Water, the three ESRs assisted in experiments of urban wastewater decontamination and disinfection. In addition, two main interesting research topics arose in the field of specific contaminants abatement and the development of innovative photocatalytic membranes, and the combination of solar wastewater treatment technologies and PV.

In the field of solar desalination, the ESRs participated in activities with the PSA Multi-Effect Distillation (MED) plant and membrane distillation facilities. They were tutored in the modelling of solar thermal power plants coupled to photovoltaic plants to jointly feed reverse osmosis and water treatment plants. They were trained in the techno-economic analysis and life-cycle analysis of cogeneration plants CSP+MED using parabolic trough collectors, not only for brine concentration but also for the recovery of materials with a high added value.

Additionally, the Materials for CST Technologies Unit has started to participate in this project in 2021, under the framework of the JRL established between DLR and METU in the field of solar reflectors (JRL3 “Optical Characterization”). In particular, some durability tests of solar reflectors were initiated by DLR and CIEMAT at the OPAC facility, including outdoor exposure in two locations and two different accelerated aging tests (UV + humidity and cupper acetic salt spray tests).

In 2021, PSA also performed on-line training activities in SolarTwins. Researchers from the PSA Units of Solar Treatments of Water and Solar Thermal Applications gave three on-line seminars included in the *ODAKtr Seminar Series* developed from December 2020 to March 2021. The PSA Unit for Line-focus Concentrating Solar Thermal Technologies gave a one-week Summer School on Concentrating Solar Thermal Technologies and their applications, explaining the basic principles and characteristics of these technologies. All these on-line sessions had a high number of attendants.

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 innovation 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 to 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 2021: During this year, CIEMAT successfully organised and coordinated several General Assembly, Management Board, and Access Manager meetings for the successful implementation of the project. Also, this year, CIEMAT organised and lunched the third call for proposals for access to the installations offered in the SFERA-III project and coordinated the evaluation of the proposals received, including the organisation of the User Selection Panel meeting for the discussion of the scores.

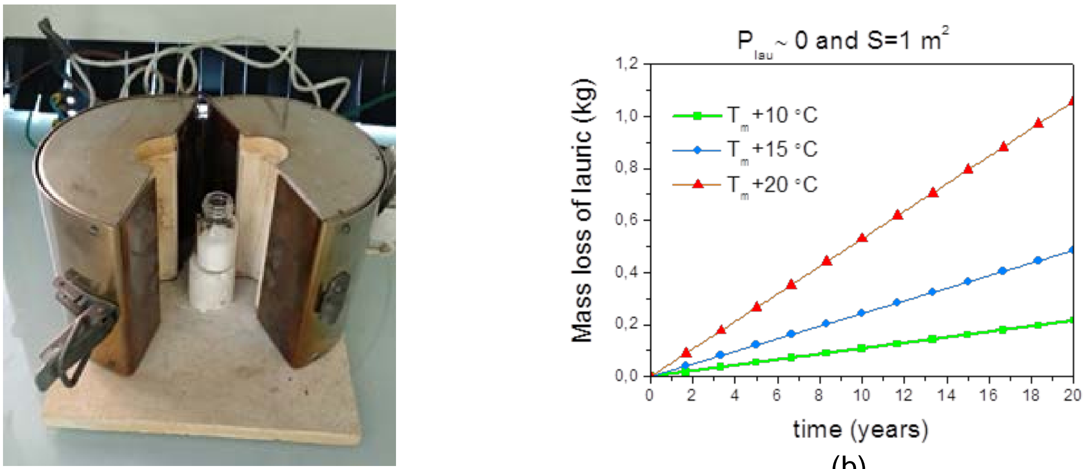
In WP1 PSA organized the 2nd SFERA-III Summer School and Doctoral Colloquium held in Almería on 5-6 October and 6-8 October 2021, respectively. The Summer School was devoted to "*Solar Process Heat Applications and Water Solar Desalination* ". The Doctoral Colloquium was organized in 5 sessions: Energy storage & solar fuels; modelling and control strategies; Solar receivers; Solar field; and Solar Energy, water, food nexus. A visit to the PSA was organised on the afternoon of 6 October to give the opportunity to both the attendees of the Summer School and the attendees of the Doctoral Colloquium to join the visit. PSA also collaborated in 2021 with DLR in the organization of the 2nd Training Course for the Industry that will be finally held in April 2022 due to the Covid pandemic. The title of this training course is "*Optimization of CST plant output by optical and thermal characterization and target-oriented O&M*".

Figure 85. 2nd Summer School (top left) and 2nd Doctoral Colloquium (top right). Visit of the PSA-facilities (bottom).

In WP3, CIEMAT, as leader of the task for the promotion of long-term sustainability, but also as responsible of the ERIC, led the work to finalise the final version of the statute of the EU-SOLARIS legal entity and the STEP 2 submission to become an ERIC. EU-SOLARIS was submitted to the hearing of ESFRI/EC committee on 28 April 2021. While in September 2021, the Spanish Ministry of Science and Innovation submitted to the European Commission the STEP2 request (prepared by

CIEMAT) for the recognition of EU-SOLARIS as an ERIC, having Spain, France, Germany, and Cyprus as members of the consortium, see section 12 for more details.

CIEMAT coordinates WP6 which is entitled Development of Test Procedures for Materials and Components of Thermal Storage Systems. Closely linked to the ACES2030 regional programme, in 2021 CIEMAT validated the HDR oven (Figure 86.a) for testing PCM degradation in terms of evaporation/gas emission and formation of coloured products. This oven has been used for studying the degradation of lauric acid under isothermal and stress conditions (T=100 - 200°C; 1 h - 2 h). By means of kinetic calculations, mass loss over time due to evaporation was predicted giving as a result that, from the evaporation point of view, lauric acid is validated as PCM (Task 6.2). Discussions on the test procedures for prototype testing continue as well as on the definition of KPIs from experimental results (Task 6.3). In collaboration with the Thermal Storage Working Group of SolarPACES Task III, which is also coordinated by Thermal Energy Storage Unit experts, a round robin test for a pressure transmitter has been proposed and accepted. This pressure transducer will be provided thanks to the collaboration of TES Unit experts have with a manufacturer (Task 6.4).



(a) (b)

Figure 86. (a) HDR oven; (b) Lauric acid mass loss prediction over years due to evaporation

CIEMAT's activity within Task 7.1 (WP7) has been focused on the definition of best procedures for exegetic analysis of MED processes. In addition, as Task 7.2 leader, in parallel with other participants, we have been working on the preliminary testing of polymeric materials for MED tube bundles. Particularly, CIEMAT is working on the establishment of the technical specifications for a new experimental facility (MED) using polymeric-based heat exchangers for MED process. Parallel to the work performed on the MED process, CIEMAT, together with the other partners, is also conducting work towards the development of procedures for Membrane Distillation (MD) and Forward Osmosis (FO) membranes testing. For the achievement of this goal, the assessment of new MD modules assisted by vacuum is being examined. In the frame of Task 7.3, CIEMAT has proposed tentative guidelines towards the performance evaluation standardization of DWT pilot plants (solar membrane distillation, nanofiltration, multi-effect desalination, CPC NOVO75). Special attention has been given to the definition of control loops and instrumentation in order to achieve the best procedures defined within Task 7.1 for the case of solar applications. Within Task 7.4 CIEMAT has been working on the development of in-house simulation software mainly related with the performance assessment of solar thermal cogeneration plants (CSP+D) coupled to MED and RO processes. Large optimization operations for thermoeconomic studies have required the development of simplified correlation models for MED plants to be able to run several thousands of yearly simulations within such optimization operations. Regarding membrane distillation, empirical correlations for GOR have been proposed for the new technology of multi-envelope spiral-wound air gap membrane distillation modules in conventional configurations.

IN WP8, CIEMAT has been involved in activities 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 has taken part in the creation of a database to guide the efforts of this task to standardise the techniques and procedures for monitoring and evaluating some key performance indicators of reactors. In Task 8.3, Dynamic Control and Automation of Solar Fuel Reactors, CIEMAT has been working on developing advanced model-based algorithms to control solar fuel systems under solar transients based on H2 production results obtained with a 100-kW cavity reactor concept. - In 2021 a modification of the control scheme based on development of a feedback linearization technique is carried out. The main idea behind the feedback linearization technique is to treat non-linear systems as linear ones by means of algebraic transformations and feedback. A control design proposed will be tested in simulation: a feedback linearization control is combined with an optimization problem. The reactor temperature is obtained with a lumped-parameter model based on physical equations.

WP9 is focused on improving services to develop and test high performance solar receiver and concretely task 9.2 deals with improving infrared temperature measurements of solar receivers. The contribution of CIEMAT in this sense has consisted in the participation in a round robin test among different partners to measure and calculate thermal emittance values of absorber samples with different properties, composition and geometries in order to compare the results obtained. In this test, thermal emittance direct measurements and indirect calculation from hemispherical reflectance measurements by using different equipment and calibration standards have been compared. While in Task 9.3 “Airbone IR measurements assessment”, the Line-Focus Solar Thermal technologies unit has analysed the results of a preliminary outdoor test campaign to determine how meteorological variables influence the measurement of the glass envelope temperature of HCEs using IR cameras, comparing laboratory and outdoor data when the absorber temperature and the vacuum pressure in the annulus of the receiver are coincident. A procedure to perform a second outdoor test campaign was decided and more results will be obtained in 2022.

In WP10, specifically in Task 10.1 “Enhancement of sensor monitoring/calibration and measurement accuracy of laboratory test benches of RI”, the Line-Focus Solar Thermal technologies unit has patented a device to measure forces and moments being applied on rotating and expansion performing assemblies of parabolic troughs. A first prototype of the system, which incorporates load cells, has been manufactured at PSA. Besides, a lab test bench has been prepared with the aim to calibrate the measurement device patented and manufactured before its use in a solar field. It is planned to have the system completely operative in 2022. Also, in this task 10.1, we have participated in the definition and preparatory work in the PSA’s laboratory of HCEs qualification of a new round robin test for increasing the quality of service of test benches for parabolic trough receivers heat lost measurement. This round robin will be developed during 2022. Additionally, in Task 10.1.A, the Materials for Concentrating Solar Thermal Technologies Unit has participated in a Round Robin Test of soiled mirrors (with CEA, Cyprus Institute, Fraunhofer ISE, IMDEA and Evora University) Artificially soiled mirrors were prepared with sand from Negev and Almería and 6 samples were optically characterized in the OPAC laboratory, in cooperation between CIEMAT and DLR, using a spectral specular reflectometer (S2R), a portable specular reflectometer (D&S 15R-USB), the Tracs device the parallel goniophotometer prototype (MIRA), and a spectrophotometer (Perkin Elmer Lambda 1050). According to the results, the soiled samples did work to some extent but for more robust results a presential workshop with handheld devices seemed essential and/or measurements with robust calibration coupons.

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, the list of e-infrastructure functionalities and services has been established, as well as the state of the art, configuration, structure and O&M specifications of the future e-infrastructure.

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 2021: This project started in June 2020 and the work of CIEMAT is committed to work packages WP1, WP2 and WP5, although our contribution to WP1 ended at the beginning of 2021. The definition of typical scenarios for the implementation of Virtual Power Plants (VPPs) within WP1 was included in the deliverable *"D1.1 Definition and specification of Dynamic Virtual Power Plant (DVPP) scenarios"*, finished on 22/02/2021.

In WP2, CIEMAT has been 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 has been built and tested in MATLAB®, including its validation with real data from commercial STE plants.

Finally, in WP5 CIEMAT has collaborated in the generation of renewable production data sets of STE plants for the operation and management of VPPs. In addition, CIEMAT has participated in the improvement of simulation models of STE plants for the economic optimization of DVPPs, sharing information of operation parameters, response times and typical features of STE plants. This work is included in the report "*D5.1 Modeling of VPPs for their Optimal Operation and Configuration"* (12/2021). Besides, a novel and simple method to generate random solar radiation profiles oriented to the uncertainty assessment of STE production forecasting has also been developed within WP5. This work has been submitted for publication in a scientific journal 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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Eduardo Zarza, eduardo.zarza@psa,es

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 which growth expectations are high. However, there is a lack of test facilities suitable for qualification and evaluation of line-focus solar collectors design 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 evaluation and qualification of small line-focus solar collectors, it has been decided to design and build a new PSA test loop 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, based in pressurized 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 PTCs using pressurized hot water up to 220°C. Additionally, the 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 2021: The technical specification for the piping, instrumentation and control systems was prepared and the components for the piping were purchased, as well as the control valves and PLC for the SCADA. The contract for the mechanical assembly was also issued in 2021. At the end of the year, the concrete platform for the installation of the water tank, water pump, water heater and the cabinets for power supply and instrumentation was built. The 3D drawings prepared in 2021 for the piping were revised at the end of 2021 to optimize the piping lay-out and thermal performance under thermal expansions, thus improving the design made in 2020. The main technical parameters finally adopted for 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·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).

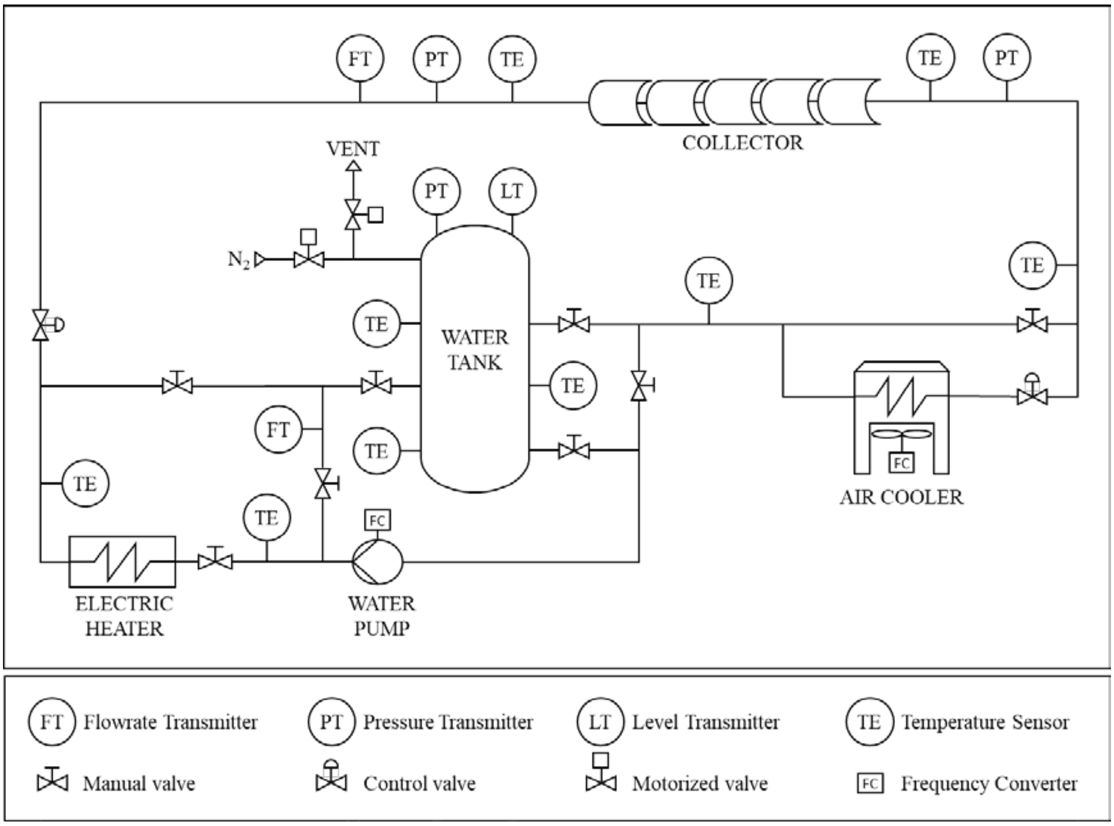


Figure 87. Simplified scheme of the LAVEC facility.

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

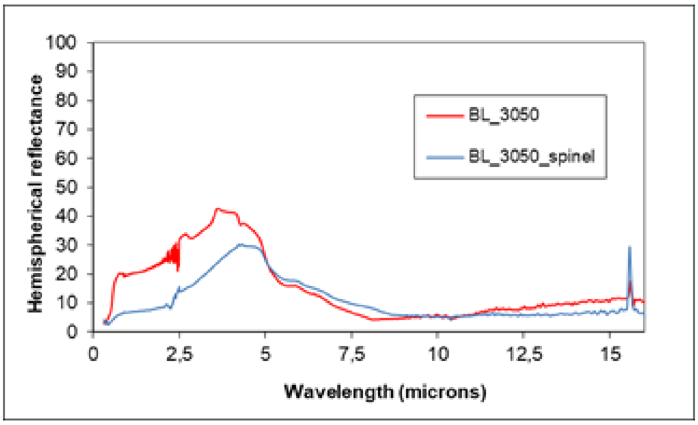
Funding agency: European Commission, EU-H2020- NMBP-ST-IND-2018-2020.

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 with highly efficient and/or innovative systems such as 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 1000°C or more in high-temperature solar receivers the use of solid particles have the advantage that they can be also directly used as the thermal energy storage media.

Objective: The project is focused on 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 aim is 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 2021: During this year, CIEMAT has contributed to the development of more efficient particles for the receiver. This has been accomplished by applying coatings on them to improve their thermal conductivity and optical properties. 8 types of particles, sized around 0.3-1.2 mm, are being considered and the application of black spinel coatings and metallic coatings by dip coating and electroless, respectively, was studied. The method for applying coatings on the particles was optimized and an increase in solar absorptance values of 4-10 percentage points was achieved with one layer of black spinel. The stability of the particle/coating system at temperatures around 1000ºC is under study.

(a)



(b)

Figure 88. Particles before and after the application of black spinel coating (a). Effect of the black spinel layer in the hemispherical reflectance of one type of particles studied (b).

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 2021: The design of the multi-tube receiver for the first prototype of an innovative linear Fresnel collector has been completed. This year, materials were gathered for the construction of the trapezoidal cavity designed for the receiver (aluminium mirrors, aluminium for the frame, heat insulation, solar glass windows, etc.). A preliminary CFD simulation model of the receiver has been developed and a parametric study on its thermal behaviour was carried out to estimate the heat losses in the receiver. On the other hand, the electronic control for the primary concentrator of the LFC prototype was installed. Both, the results of the CFD simulation of the receiver and the characteristics of the control system designed and installed, were presented in two separate presentations at the SolarPACES 2021 conference. The development of a selective coating stable in air for medium temperature applications was completed (absorptance > 0.95 and emittance@350°C < 0.10); the durability of the coating was also completed with no degradation of the optical properties observed after 15 months of testing. A new selective coating for high temperature (700°C) applications was also developed with a solar absorptance of 0.95 and a thermal emittance at 700°C of 0.20. Thermal stability after 2 months at 700°C was not affected. The antireflective coating developed to be applied on the receiver quartz window has been optimized. The quartz solar transmittance value was increased from 0.93 to 0.98 after its application. The durability of these coatings was studied by abrasion tests with a linear abrasive tester and a sand oscillating device. All the results showed that more resistant coatings are obtained when using sintering temperatures around 700°C without decreasing the high solar transmittance values. Laboratory developed prototypes were tested in a 7-kW solar simulator observing no degradation of the windows after testing (Figure 89). With CFD software, a parametrical study about the thermal and hydrodynamic influence of the absorber's physical design within a standard cup were comprehensively analysed and the results were presented in SolarPACES 2021. Moreover, a detailed analysis of the heat transfer coefficient in wire mesh volumetric receivers was carried out and the main conclusions were presented in SolarPACES 2021, ISES 2021 and 1st ARE. With simulation models developed in TRNSYS, the integration of iLFC-solar fields in two industrial processes: pasteurization and brewing, was simulated. The studies included performance comparisons to flat-plate collectors. A preliminary economic analysis suggests that the iLFC concept may achieve lower values of Levelized Cost of Heat that other technologies when the cost of industrial land is higher than 60 €/m^2. The results were presented at the SolarPACES 2021 conference. Regarding Task 4.3, a comparison in terms of energy efficiency and water production of two solar cogeneration plants was performed. The solar cogeneration plant consists on a Central Receiver CSP plant with a combined cycle formed by a solar-hybrid gas turbine system plus a Rankine steam cycle and two integrated desalination systems: 1) a low-temperature multi-effect distillation (LT-MED) unit and 2) a reverse osmosis unit. The results were presented in ICP 2021 "Sixth International Conference on Polygeneration" and the paper was selected to be sent to a Special Issue of Energy Journal. Also, the development of an heliostat field model in SolarPILOT and central receiver system in Modelica has been carried out, coupling together with the previous developed Brayton cycle model and online input data to simulate the system and generate interactive results on a web app which is currently under development (see Figure 90).

Figure 89. Uncoated quartz window and AR coated quartz window (right) and window assembly in the 7 kW solar simulator testing bench (left).

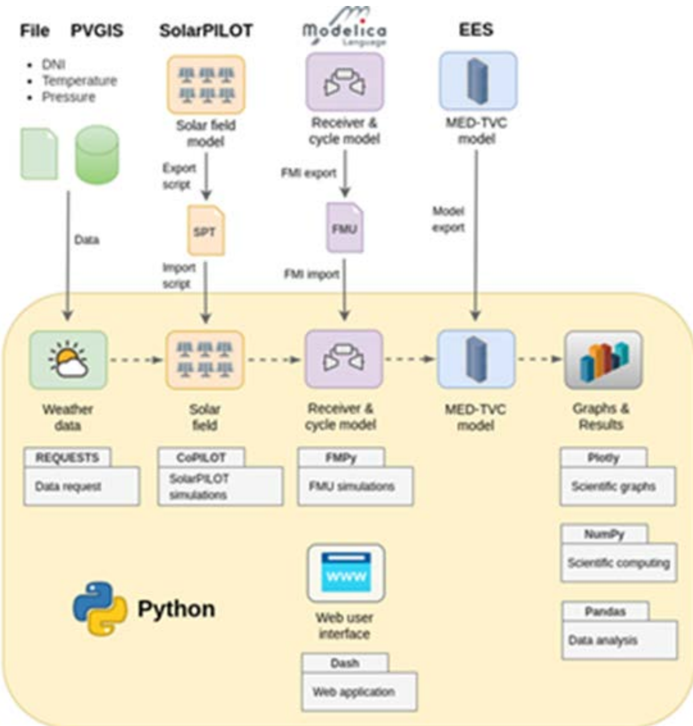


Figure 90. Scheme of the software tool to simulate solar cogeneration plants composed of central receiver CSP plants and desalination systems.

Silicone Based HTF in Parabolic Trough Applications - Preparation of a Guideline, Si-HTF Guideline

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

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

Funding agency: SolarPACES (International Energy Agency).

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: The project aims at forming an international expert work group with the assignment to elaborate an experienced-based guideline for the admission of silicone based HTF (SHTF) in PTC applications. The guideline shall be the basis for future international standardization activities in the same field. The project has a duration of 18 months and comprises three main phases: Data compilation, Admission procedure comparison and Guideline document.

Achievements in 2021: The project started in April 2019 with the activities and data compilation planned in WP1, i.e., the formation of the expert work group; a detailed summary of the qualification procedure executed for silicon heat transfer fluids (HTFs) and the compilation of standards and other existing documents applicable to the use of HTFs in solar thermal systems.

Most of the development work was then performed by the partners in 2020, so version V1 of this guideline was published in February 2021 after a last review by the partners, thus concluding the activities planned in this project. The guideline is published and available for free download in the SolarPACES webpage. This guideline is open for comments.

The guideline available at the SolarPACES webpage is a 75-page document covering all the main aspects related to silicone oils (fluid composition, thermal stability issues, heat transfer issues, safety relevant parameters, fluid compatibility and test methods)

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

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

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

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 2021: 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, which allowed to continue with the elaboration of the contents of the standard by the expert's group involved in the SolarPACES project. According to the work plan defined in the project, the draft for the standard was almost completed by the end of 2021. This draft will be circulated for final revision among the experts involved in the SolarPACES project and it is expected to send the first draft for circulating at IEC TC 117 level in March 2022.

The reference of this new IEC standard is 62862-1-6 and the index of the draft document proposed includes inspection and sampling procedures, qualification procedures, packaging, transportation, storing, mixing with other thermal oils, recycling and disposal.

REPA testing at the HTF test loop

Participants: ROTARM, CIEMAT.

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

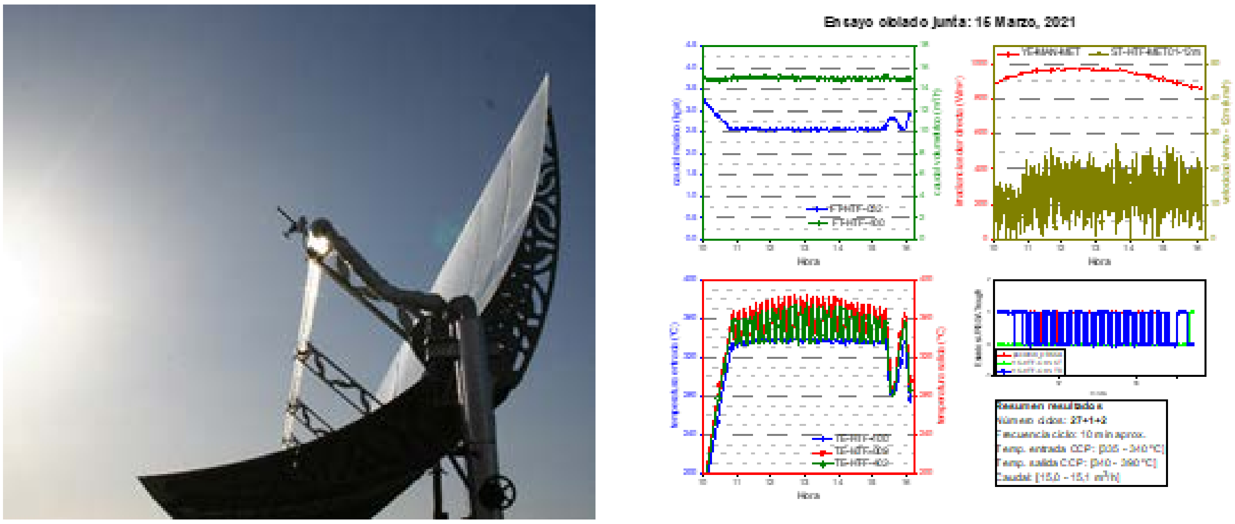
Funding: R&D contract – ROTARM (May 2019-Jul 2021)

Background: Rotation and expansion assemblies are key components in parabolic trough power plants. The qualification of this type of components, especially its lifetime performance is currently a critical issue to plan and predict O&M costs in existing power plants.

Objectives: Testing and qualification of a rotary flex hose assembly, composed of a flex hose and a swivel joint, designed and manufactured by the Spanish company ROTARM. The objectives of the bilateral project are:

- Installation and continuous testing of a rotary flex hose assembly in the outlet of a standard parabolic-trough collector of the HTF test loop at Plataforma Solar de Almería.
- Thermo-mechanical cycling of the unit for qualifying its service live time.

Achievements in 2021: The testing of the rotary flex hose assembly installed at the outlet of the URSSATrough collector of the HTF test loop was completed in May 2021. More than 5000 cycles of the flex hose were completed, being this number considered sufficient at that moment by the company to start the commercialization of the product designed. The test campaign defined and executed by CIEMAT has included the following types of thermo-mechanical cycles of the kinematic units working at nominal operating conditions: (i) 85% of short cycles (rotation=±11°, temperature step=40/50°C); (ii) 5% of intermediate cycles (rotation=±90/100°, temperature step=100°C); and (iii) 10% of long cycles (rotation>120°, temperature step=start/stop of the solar field). Figure 91 shows a view of the kinematic joint, which is installed at the outlet of the URSSATrough parabolic trough of the HTF test loop, and an exemplary graph of a typical day of testing at the HTF test loop.



(a) (b)

Figure 91. (a) View of the kinematic joint from Rotarm installed at the HTF test loop; (b) example of process data (HTF flow rate, HTF temperature, available direct solar radiation, wind speed, tracking/phase order) during a cycling test of the kinematic joint. Date: March 15, 2021.

Soiling measurement of solar reflectors

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

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

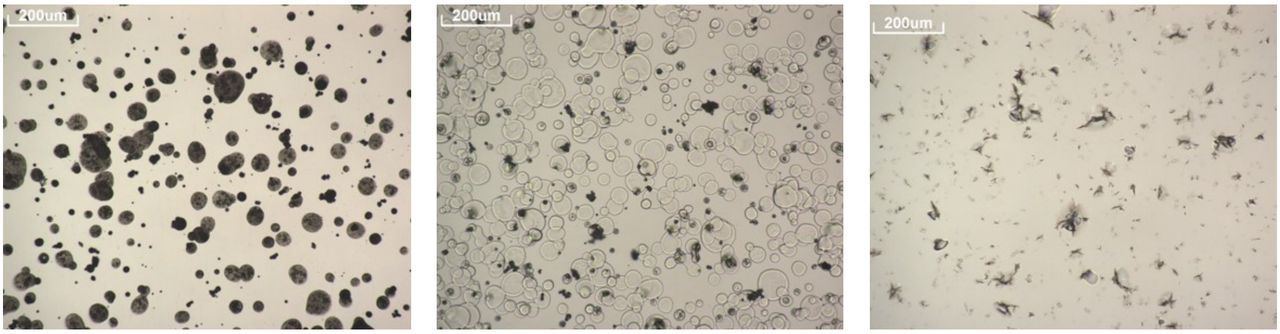
Funding agency: SolarPACES (International Energy Agency).

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 2021: During 2021, all activities linked to WP1 were completely ended and the corresponding deliverable (titled “Portable reflectometers to measure soiled reflectors in solar fields”) was finished. This report includes the main features of the marketed reflectometers and was prepared using information from the manufacturers’ documentation, researchers’ knowledge, and plant operators’ experience. Also, the main practical difficulties faced by plant operators during the field measurements and the list of desired features for the ideal instrument were addressed. In addition, data collected from previous experiments performed to compare field portable reflectometers was analysed.

With respect to WP2, which is devoted to obtaining correlations between portable and advanced lab instruments, several coupons with well-defined opacities that simulated the optical behaviour of naturally soiled reflectors were prepared. The coupons were manufactured by applying several different methods to silvered-glass reflector samples (see Figure 92), such as spraying black paint, spraying hairspray, introducing the samples in a sand blast chamber, fixing particles with hairspray and enclosing particles between a glass sheet and the reflector. These coupons were measured both with portable and laboratory equipment by different institutions (CIEMAT/DLR, ENEA, Fraunhofer ISE and University of Zaragoza) to estimate conversion functions that allowed to derive more representative reflectance values from the data acquired with field instruments. All the information collected during the measurement campaign was compiled to prepare a new guideline with recommendations for reflectance measurements on soiled mirrors.



(a) (b) (c)

Figure 92. Microscopic view of sprayed black paint (a), sprayed hairspray (b) and sand blasted (c) samples.

Solving Water Issues for CSP Plants, SOLWARIS

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

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Eduardo Zarza Moya, eduardo.zarza@psa.es

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

Background: Water consumption is a major issue for the commercial deployment of CSP/STE plants in desertic 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 of the work initiated in WASCOP.

Objectives: The main objective of SOLWARIS is the testing and validation in a real commercial environment of important innovations for water saving in CSP/STE plants. These innovations include: anti-soiling coatings for mirrors and receiver tubes, advanced 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 2021: In WP3, CIEMAT has completed a study of a hydrophobic anti-soiling coating on the glass tubes of RIOGLASS receivers (subtask 3.4.3). In addition, CIEMAT has studied the effect of the coating on the optical properties, the abrasion resistance and the durability under condensation conditions in CIEMAT laboratory by testing samples of commercial tubes. The results showed that the coating was stable under the conditions tested and variations in abrasion behaviour were observed by the anti-soiling treatment. CIEMAT has also concluded the assessment of the durability of the anti-soiling coating for reflectors developed by IK4-TEKNIKER and RIOGLASS (subtask 3.4.2), by testing coated samples under accelerated aging conditions.

In WP5, work has focused on the development of the dynamic model of the multi-effect evaporation plant for water recovery purposes in a CSP plant, which has been implemented in Dymola software. All components of the plant have been modelled (bundle tube of each effect, steam ejector, desuperheater, cyclonic box of each effect, final condenser, plate heat exchangers, mixed tank). Likewise, the model has been validated with data given by the manufacturer (INDETEC), obtaining a good agreement between the results of the model and the design data. Finally, a sensitivity analysis was carried out, in which the dynamic response of the system against disturbances was in the main operating variables. This has been reflected in a paper that was sent to the SCI journal Desalination at the end of 2021.

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

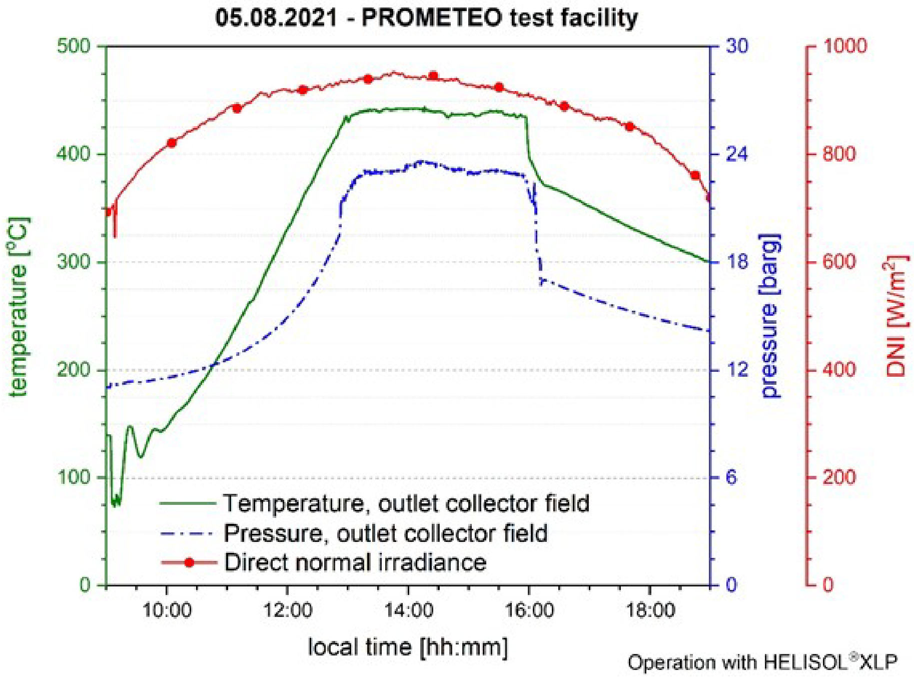
Contacts: Loreto Valenzuela, loreto.valenzuela@psa.es

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 to define the characterization procedure for this type of oils. The development, testing and demonstration of 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 2021: The proof of concept of the heat transfer fluid HELISOL®XLP manufactured and supplied by Wacker Chemie AG at the PROMETEO pilot plant under real solar conditions started in February 2021 within the scope of the SING project. Between February and December, the plant was operated for 900 hours; for 215 hours out of the total 900 operating hours, HELISOL®XLP was working between 425°C and 440°C. Nine gas and eight liquid samples were extracted from the PROMETEO plant and sent to Germany for characterization by the German Aerospace Center (DLR) al Koln. The following project and the maintenance related activities were performed by CIEMAT: legalization of the PROMETEO plant by the Spanish ministry of Industry, localization and fixing of gas and liquid leakages due to thermal cycling, close follow up of key components at the oil circuit of PROMETEO plant: Heat Collector Elements (HCE) and Rotation and Expansion Performing Assemblies (REPA), mainly.



(a)

(b)

Figure 93. Main parameters during a test with HELISOL®XLP (a) at the PROMETEO test facility (b).

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 different test procedures towards a documented uniform test cycle (to be documented in the REPA testing guideline), which will be the basis for the preparation of an international standard later. 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 2021: In the scope of the REPA Guideline project, the PSA REPA-testig facility has been operated and maintained by the CIEMAT early in 2021 at 450ºC not only for the aging of the new Si-HTF HELISOL XLP®, from WACKER® industries, reconditioning but also for SeniorFlexonics REPA prototype accelerated aging. Both tests were finalized in February 2021 when the REPA swivels joints started leaking. The HELISOL XLP® has been operated 700h at 450ºC. Late in 2021, the operation at REPA was resumed with a new set of swivel joint and flexible hose prototypes from SeniorFlexonics and the HELISOL XLP was exchanged for the most used HTF in commercial solar thermal power plants, the eutectic mixture Therminol VP1.In the meantime, CIEMAT executed maintenance activity of the REPA facility, and in collaboration with the DLR, looked to increase the reliability of the load cell sensors used to measure the torque and forces in the samples under testing. To do so, after the initial validation test, a systematic investigation and segregation of geometrical, thermal and hydraulic influences on the measured load was undertaken. Different influences on the loads such as system pressure, HTF temperature, and REPA motion were segregated and recorded individually. The results were published in a scientific paper which was presented at the SolarPaces conference 2021 with the tittle “Segregation of influences on flexible pipe connectors (REPA) force under field operation condition for parabolic trough collector plants”.

Figure 94. 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 2021: The project was officially launched in April 2021. CIEMAT will contribute 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 2021, CIEMAT has started preparatory works to review the general status of the Balance of Plant of the PTTL test facility, where the demonstration will take place, including functional tests of all the equipment, i.e., pump, gas-heater, air cooler, automatic valves, instrumentation, etc. ACCIONA, TEWER and CIEMAT have met at PSA this year to discuss about the assembly and to coordinate the upgrading and modifications needed at the PTTL test facility. At the end of the year, Wacker Chemie AG supplied the required Si-HTF, 20 IBCs of 900 liters/each of HELISOL®XLP, to replace the existing heat transfer fluid in the facility. CIEMAT and DLR also agreed on the collaboration to supply HCEs units to DLR to be contaminated with H2, that will be measured before and after the continuous field testing planned at the KONTAS test facility of the PSA. The heat loss measurements of these HCEs will be performed by CIEMAT at the receiver tubes lab at PSA.

Figure 95. View from the South of the balance of plant of the PTTL test facility, with the IBCs of the new Si-HTF to be tested ready on-site.

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.

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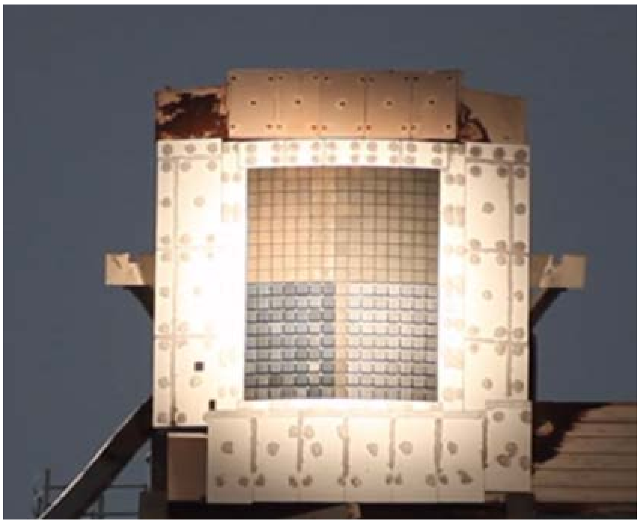
Funding agency: European Commission, H2020-NMBP-2016-2017. Grant Agreement no. 721045

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. While 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 the maximum working temperatures and in-service overall durability, mainly due to failure by thermal cycling. 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. The actual exploitation of the hotter air (up to 800°C) is then crucially tied to the development of a high temperature thermal storage, here inspired by nuclear fission GEN-IV technology and based on liquid lead by means of new corrosion resistant steels.

Achievements in 2021: In this final year of the project, 2 of the different volumetric absorbers' configurations tested previously on the solar furnace were installed on the CESA-I tower. This way it is possible to compare the new solutions with the state-of-the-art volumetric absorber behaviour in terms of durability and thermal performance. Preliminary results are promising, showing longer life cycle than current technology as well as an improvement of the thermal behaviour choosing gradual porosity prototypes.



(a)

(b)

Figure 96. Testing the new volumetric absorber solutions installed on the CESA I volumetric receiver facility. Left, monolithic new formulation SiC technology, and right gradual porosity design details.

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. 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.

Results in 2021: 2021 was the starting year of the project and the tasks performed during this first stage have been the installation of the different sensors on the solar field:

- 3 anemometers fix mast installed at different positions into the solar field.
- 1 mobile anemometer mast for measuring special points into the heliostat field.
- 2 LIDAR on the surrounding of the solar field for building up a high spatial resolution wind field profile.

Anemometers are already installed on the solar field and they have started to feed the wind database that will allow the development of the different wind profile models.

Figure 97. View of the wind mast installed in the west side of the CESA-1 solar field.

PV plant with thermal cogeneration, SOLARBLUE

Participants: MAGTEL, CAPSUN, CSIC, CIEMAT, GHENOVA.

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Funding agency: CDTI, FEDER - INNTERCONECTA 2018.

Background: CAPSUN Technologies and GHENOVA Ingeniería have jointly developed a disruptive technology that integrates the best characteristics of Photovoltaic Plants (PV) and Concentrated Solar Plants (CSP). By means of a selective optical filter, the light spectrum is divided. The filter allows the efficient passage of radiation used by the photovoltaic panel (mainly visible light) while reflecting 40% of the energy (mainly blue light and infrared). Selective filters were validated by CIEMAT in a former project (SPIRE).

Objectives: As a continuation of the SPIRE project, SOLARBLUE aims to demonstrate the, among other aspects, the concept of hybrid heliostat, that generates electricity due to the PV panels installed and, at the same time, reflects part of the solar spectra (mainly Blue and Infrared wavelengths) to a solar receiver. The role of CIEMAT in the project is the optical and energetic characterization of a 40 m^2 prototype that will be installed on CESA-I solar field at PSA.

Achievements in 2021: A whole heliostat prototype (40m^2) has been equipped with 1m^2 size PV SOLARBLUE panels (coated with the selective layer) in order to check the manufacturing process as well as concentrating and PV performances. The following results can be highlighted:

- PV panels allow the canting procedure of the heliostat. A focal distance can be achieved to concentrate solar radiation on the target.
- Selective coating reflects the blue and infrared wavelengths to the target resulting in a lower temperature operation of the PV cells, improving I-V performance.
- Reflected radiation can be focused, allowing the prototype to heat up materials and fluids on the target.

Figure 98. SOLARBLUE heliostat prototype.

Solar extinction measurement system commercialization – Ref. 8510/2018

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

Contacts: 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 solar concentration 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 solar collectors to the receiver in a tower plant. In order to respond to the demand for this measurement system by companies in the solar concentration sector, knowledge about this system will be transferred to the BCB company with the consequent economic consideration to CIEMAT for each installed system.

Achievements in 2021: As a result of the technology transfer contract to the Spanish engineering company BCB, the first commercial atmospheric extinction measurement system has been implemented in a 100 MW commercial power tower plant and using molten nitrate salts at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai (United Arab Emirates).

Storage Research Infrastructure Eco-System, StoRIES

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

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Funding agency: European Commission, 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, providing a back-up to intermittent renewable energy and contributing to seasonal energy storage challenges. Above all, the main challenge for energy storage development is economic.

Objectives: The main objective of StoRIEs is to create an industrial and research ecosystem at European level in the field of energy storage by providing access to high-level research infrastructures and services as well as the development of specific services focused on the improvement of materials and the optimization of hybrid energy systems. The StoRIEs project also includes the analysis of the socio-technical and environmental aspects of such systems, the identification of potential industrial users, as well as training activities and the preparation of roadmaps.

Achievements in 2021: In November 2021 the project was launched in coordination with EERA JP ES steering committee meeting (JPES SCM-19) alongside the Joint StoRIES-JPES-SUPEERA workshop prior to the project kick-off meeting. It was organised in hybrid mode, with a group of participants attending the conference live (Karlsruhe, DE) and a group attending online.

Small-Scale Solar Thermal Combined Cycle, POLYPHEM

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

Contacts: Esther Rojas, esther.rojas@ciemat.es

Funding agency: European Commission, H2020-LCE-2016-2017

Background: With the objective of increasing the flexibility and improve 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 2021: The main contribution of CIEMAT is on the thermal storage system (TSS). Thermal Energy Storage Unit coordinates the WP for the design and simulation of the TSS. This TSS is a thermocline tank with filler. During 2021, the experiments carried out in the MicroSol facility have been analysed. Heat transfer coefficient enhancement between the oil and concrete have been found in comparison with the current heat transfer models correlations. Severe problems to go on with the erection of the TES tank were faced due to the lack of time for it and the required, but undesirable for one of the industrial partners, extension of the project. A compromised solution was finally found with a 5-month extension of the project.

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

Participants: IMDEA-Energy (coordinator), CIEMAT, CSIC, UC3M, UNED, UPM, URJC, PROTERMOSOLAR (associate partner), Empresarios Agrupados (associated partner), Abengoa Energía (associated partner), Grupo Cobra (associated partner), Rioglass Solar (associated partner), REPSOL (associated partner).

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Alfonso Vidal, alfonso.vidal@ciemat.es

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

Background: Three main challenges covering aggressive penetration of CSP within end use energy mix by 2030: Renewable electricity where a new class of better CSP plants are required; Solar process heat where technologies and integration schemes are required; Solar fuels for transport, where materials, technologies and processes for the H_2 production and storage are required.

Objectives: Challenges to improve CSP within end use energy mix by 2030 are approached through 4 R&D lines: (i) optical engineering; (ii) solar receivers and reactors together with the corresponding materials and thermal fluids; (iii) energy storage systems; and, finally, (iv) the analysis of integration of thermodynamic cycles and industrial processes.

Achievements in 2021: CIEMAT focusses on two main activity lines: one focusses on defining the methodology to validate phase change materials as latent storage material and another one on packed bed thermal storage at high temperature with atmospheric air as heat transfer fluid.

In the first line, during 2021, CIEMAT validated the HDR oven for testing PCM degradation in terms of evaporation/gas emission and formation of coloured products. This oven has been used for studying the degradation of lauric acid under isothermal and stress conditions (T=100 - 200°C; 1 h - 2 h). The obtained experimental data were treated afterwards using kinetic calculations, showing that, from the evaporation point of view, lauric acid can be considered an acceptable material for latent storage. The analysis of the thermogravimetric measurements (TGA) of some fatty acids has gone on. In addition, in order to obtain information on the thermal degradation of these acids in conditions as close as possible to those of operation, isothermal weight loss tests have been carried out for lauric acid using an oven and sample quantities between 1 g and 5 g. In general, it has been observed that the kinetic results obtained by both methods (TGA and furnace) differ considerably because they are greatly affected by the amount of sample used in the tests. Therefore, it is necessary to jointly analyse both types of results in order to determine the degradation kinetics of these PCMs in real operating conditions and therefore predict their long-term behaviour.

In the second line, the comparison of experimental results between natural materials, formerly considered suitable at the operation temperature tested, shows the need of testing the materials not only in oven but also in working conditions similar to those of real operation, since one of the materials becomes decayed, due to the direct contact with the hot air flow. A ceramic material has also been tested in ALTAYR test bench up to 850°C, observing no degradation at all

The contribution of CIEMAT to the present project is focused on the development of new materials for thermochemical cycles aimed at clean hydrogen production. The various materials being studied include ABO3-type perovskite materials that improve the redox characteristics of the materials most commonly used to date, such as Ni ferrites ($NiFe_2O_4$), as well as materials based on Cerium oxide (CeO_2) that allow the high activation temperatures for this material (1400 – 1600°C) to be reduced.

Thus, the following perovskite-type materials A1-xA′xByB′1-yO3 with doping in the A and B positions have been synthesized.

- $La_{0.6}$ $Sr_{0.4}$ $Fe_{0.8}$ $Co_{0.2}O_3$, and $La_{0.2}$ $Sr_{0.8}$ $Fe_{0.8}$ $Co_{0.2}O_3$
- $La_{0,6}$ $Sr_{0,4}$ $Fe_{0,8}$ Co $_{0,2}$ O_3, and $La_{0,6}$ $Sr_{0,4}$ Fe O_3

Structural studies were carried out by X-ray diffraction (XRD). Phase identification was performed by comparing the acquired data with reference databases using HighScore Plus software. Thermal analysis of the materials is being performed by thermo-gravimetric analysis (TG) and differential thermal analysis (DTA) using a simultaneous thermal analyser Netzsch STA 409.

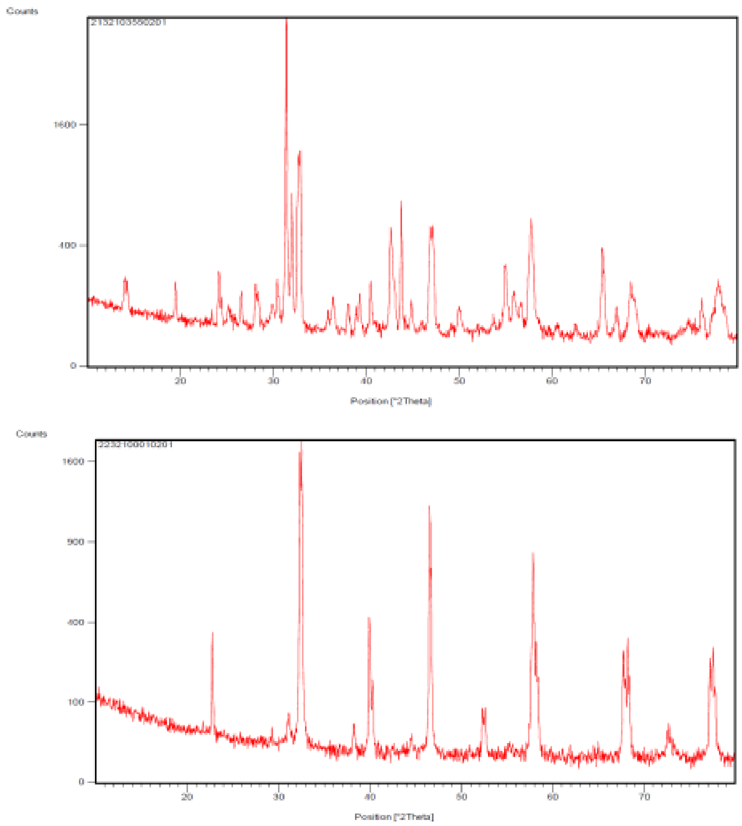

Figure 99. Diffractograms corresponding to two samples of LSF obtained by the coprecipitation (a) and Pechini (b) methods.

Figure 99 shows the diffraction patterns of the perovskite $La_{0.6}Sr_{0.4}FO_3$ synthesized by the co-precipitation and Pechini methods. From these data, the analysis of the diffractograms corresponding to the LSF sample prepared by co-precipitation and calcined at 1200°C shows the presence of a great variety of crystalline phases that could correspond to secondary phases obtained from the respective precursors used, which are not integrated in the main structure, which seems to indicate that the method is not adequate to achieve the formulation of the material sought. However, the diffractogram of the LSF material prepared by the Pechini method shows the presence of a single crystalline phase with the LSF perovskite-type structure.

Compared to the co-precipitation method, the Pechini method allows obtaining powders with compositional homogeneity and nanometric particle sizes, which are the desired characteristics for this type of applications.

Characterization of optical properties of particles for CSP.

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

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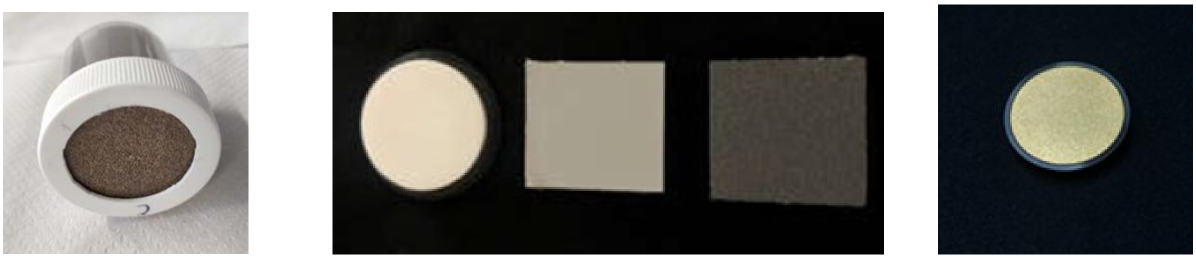
Funding agency: SolarPACES (International Energy Agency).

Background: The application of particle receivers in high temperature CSP 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.

Objectives: The main goal of this project is to define a proper protocol to characterize optically particles. With this aim, a round robin test (RRT) for measuring particles of different properties with different methodologies and equipment is being done. The influence of the packaging of the particles and the particle size is being investigated. From the RRT, discrepancies and errors will be identified, and a proper measurement protocol and calculation procedure will be stablished. A guideline for solar absorptance particles and thermal emittance measurement and calculation will be published with the results obtained.

Achievements in 2021: During 2021, the procedure to obtain the solar absorptance and thermal emittance of the particles was defined. Particles with different characteristics in terms of particle size and composition were selected and supplied for testing. CIEMAT coated nine batches of particles with black spinel pigments in order to modify their optical properties and they were supplied to all the partners of the project for the characterization. The measurements are being collected to compare the results obtained by all the partners.



(a) (b) (c)

Figure 100. Particles holder to be placed in the UV-VIS spectrophotometer (a) and diffuse reflectance standards used to measure in solar spectral range (b) and infrared range (c)

Recubrimientos Innovadores Preparados con Magnetron Sputtering para Absorción Solar Selectiva (HiPIMSolar)

Participants: Instituto de Ciencia de Materiales de Sevilla ICM-CSIC (coordinator), CIEMAT.

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Inmaculada Cañadas, i.canadas@psa.es

Funding agency: Junta de Andalucía. PAIDI 2020. Ayudas I+D+I en Universidades y Centros de Investigación Públicos. Convocatoria 2018. Referencia. P18-RT-2641.

Background: The development and improvement of materials used in medium and high-temperature CSP systems is increasing their efficiency, making them more competitive and cost-effective. Recent research works aim to develop new, high-temperature stable, selective solar coatings that improve the performance of CSP plants. The aim is to maximise absorption in the visible and near-infrared region and minimise thermal emissivity in the far-infrared.

Objectives: HiPIMSolar project aims to develop new selective absorber coatings suitable for CSP systems at higher temperatures than the materials currently used. The coatings are being prepared as multilayers by the novel sputtering technology where the different materials are evaporated by means of high energy pulses (HiPIMS - High Power Impulse Magnetron Sputtering). Subsequently, their behaviour will be studied under solar real conditions by thermal ageing at a solar furnace.

Achievements in 2021: CIEMAT is involved in tasks 3 and 4, related to the evaluation of the optical behaviour as well as the durability and thermal stability testing of the coatings in solar real conditions. Relating to these tasks, CIEMAT has collaborated in the optical evaluation (UV-Vis e IR) of the first batch of selective coatings developed by ICM-CSIC carried out in the Advanced Optical Coatings Laboratory - OCTLAB. A new generation of improved samples are being developed at ICM-CSIC, to be evaluated, selected and further tested under isothermal and accelerated solar ageing campaigns at PSA SF40 Solar furnace.

Desarrollo de Materiales Cerámicos Avanzados para Aplicaciones Energéticas (CERAMITECH)

Participants: Instituto de Tecnología Cerámica - Asociación de Investigación de las Industrias Cerámicas (ITC-AICE) (coordinator), CIEMAT.

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José Rodriguez, j.rodriguez@psa.es

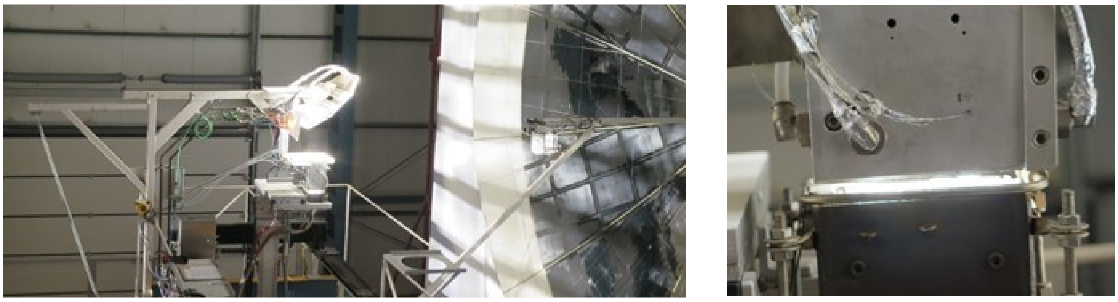
Funding agency: Service Contract Ref. CIEMAT: 10337/2021, funding by Generalitat Valenciana, Instituto Valenciano de Competitividad Empresarial, IVACE, para potenciar la excelencia en materia de I+D (2021) Ref. IMAMCA/2021/1

Background: CIEMAT-PSA has a wide experience in the isothermal and accelerated testing of advanced ceramic materials, under high solar flux conditions, using solar furnaces, mainly developed under the H2020-NEXTOWER Project. CIEMAT has developed a test bench for ageing advanced ceramic materials under high solar flux conditions, and a methodology described in the CEN-CENELEC Workshop agreement "CWA 17726 High temperature accelerated ageing of advanced ceramic specimens for solar receivers and other applications under concentrated solar radiation" (2021).

The Institute of Ceramic Technology (ITC-AICE) is researching for advanced ceramic materials for different industrial applications.

Objectives: The CERAMITECH project aims to study advanced ceramic materials for their application in the energy industry. The project studies the behaviour of different materials previously processed, such as SiC, Al_2O_3, ZrO_2, among others, as highly sintered ceramic materials, with good mechanical and thermal properties. After the development, processing and analysis of different materials by the ITC-AICE, the ceramic materials with the best behaviour in conventional heating will be selected for their study under concentrated solar real conditions, for its future application in volumetric receivers used in point focus concentrating solar systems. A service provision contract establishes the framework for CIEMAT to carry out the research work related to the CERAMITECH Project.

Achievements in 2021: During this period, isothermal and accelerated solar ageing tests were carried out on advanced ceramic samples, developed by ITC-AICE, with different characteristics in the SF40 furnace at CIEMAT-PSA. Ceramic materials reached temperatures of up to 1200°C in order to determine their behaviour and durability under conditions of high solar energy fluxes. Afterwards, optical evaluation (UV-Vis and IR) has been carried out in the durability and characterization of materials under concentrated solar radiation laboratory (MaterLab). The final goal is to validate their potential use as ceramic absorbers compared to commonly used materials, such as SiC, in point focus CSP applications.



(a) (b)

Figure 101. Accelerated ageing testing of advanced ceramics materials at Solar Furnace SF40. (a) AATB - Accelerated ageing test bench working. (b) Ceramic materials under solar testing.

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

Participants: APTL, DLR, Hygear ENGICER SA, SCUOLA UNIVERSITARIA PROFESSIONALE DELLA SVIZZERA ITALIANA, COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES, ABENGOA HIDROGENO SA, CIEMAT.

Contacts: Alfonso Vidal, alfonso.vidal@ciemat.es

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

Background: 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 below:

- Improvement of the stability, cyclability and performance of the redox materials and redox structures (1000 cycles or 5000 hours of operation),
- Design novel solutions for high temperature solid-solid and solid-gas heat recovery. Heat recovery rates substantially higher than 50% are requested to meet that target,
- Embed and validate smart solutions to minimize the consumption of auxiliaries like flushing gas. Target should be to reduce energy losses through such auxiliaries to less than 25% of the energy output,
- Design and development of intelligent systems and a smart process of control and automation, including predictive and self-learning tools, and
- Demonstrating that long-term performance of materials and key components under realistic boundary conditions using existing solar test facilities is needed (core components like the solar receiver in a scale of about 500 kW). Testing period of the hardware, minimum 6 months.

Achievements in 2021: During 2021, tests were focused on analysing the efficiency of the thermochemical process by using different ways of operation. During a first step at high temperature, the metal oxide $NiFe_2O_4$ is reduced by releasing O_2,thus creating oxygen vacancies in the structure. In a second step at lower temperature, the non-stoichiometric oxide ($NiFe_2O_4$) is re-oxidized with H_2O, leading to the production of H_2. This temperature-swing operating mode requires high temperatures during the reduction and a temperature gap between the two steps, which impacts the solar-to-fuel efficiency. A comparison between the two operating modes, namely isothermal versus temperature-swing cycle, was performed in the east module reactor integrating NiFe2O4 porous foams.
Some preliminary tests were carried out to be familiar with the general thermal behaviour of the cavity and to define and optimize a control strategy to heat up and cool down the reactor. To operate the cavity on this mode, the number of heliostats focused on the modules was manually modified to reach the desired power requirements. Some heliostats were moved to standby to accelerate the cool down, and on the other hand, to heat up, additional heliostats were focused to facilitate the switch over, which can also be understood as a decrease in DNI (Normal Direct Isolation). Cycling temperature was 1100°C for regeneration and 850°C for hydrogen production.

As an example, the hydrogen production cycles of two test weeks' tests in September 2021 are shown in Figure 102. It can be stated that operating the module in a swing mode led to higher hydrogen production rates. Steam concentrations in the feed stream were constant at 4 kg/h, except one in which the steam concentration was double.

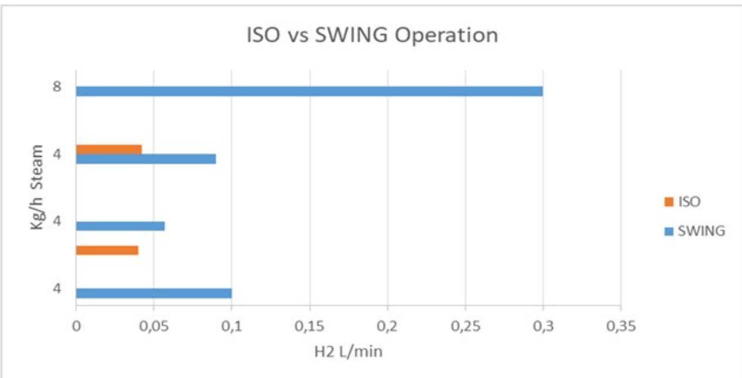


Figure 102. H_2 production in swing vs isothermal operation.

It can be stated that operating the module in a swing mode leads to higher hydrogen production rates. Obviously, operating the cavity non-isothermally will lead to thermal stress and fatigue on the active and structural materials when compared to isothermal approach. A durability test inspection was implemented at the end of the tests although a more in-depth study achieving at least 1000 cycles is scheduled in the project.

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

Participants: Space Applications Services (Belgium), CIEMAT-PSA (Spain), Airbus Defence 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 with the purpose of demonstrating In-Situ Resource Utilization (ISRU) on the lunar surface. ISRU means that *local* resources, especially minerals, are used to produce useful goods like air (oxygen), water, metals, construction materials, or rocket propellant. To prepare the mission, ESA issued several ITTs (Invitations To Tender) to do detailed preparatory studies. This project was among the selected participants. It's the follow-up project of the Alchemist-project (ESA-Contract ITT AO-9107) carried out in 2018.

In the years before, at the Plataforma Solar de Almería (PSA), a full-scale test plant able to reduce ilmenite (a common mineral on the Moon) with the help of 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 of PSA to be invited to participate in the ITT.

The project ALCHEMIST was the first ESA payload study that defined the high level details of a lunar ISRU payload. The concept chosen for operation was the hydrogen reduction process.

Objectives: The principal goal was to define the hardware of a hydrogen reduction plant operating on the Moon. This included the sub-systems for excavation of the lunar sand (regolith), the pre-processing like sieving or enrichment, the processing of the regolith with hydrogen at 900°C, and the fluid management for the hydrogen supply, recirculation, and extraction and storage of the product water. Goal of the mission is to produce 100 g of water from lunar regolith.

Achievements in 2021: Originally it was planned for the Alchemist project to end in April 2020. Due to some delays, the final project presentation meeting was delayed to January 2021. Nevertheless, the work with the fully developed and operative Oresol reactor continues at PSA. The main objective of the tests is to advance in development of the technology and to obtain much more in-depth operational and scientific data for further Alchemist editions. Due to the Covid-19 pandemic, there were no solar tests during neither 2020 nor 2021. But the time was used to continue with the data evaluation. The results obtained for the five goals of the project can be summarized as follows:

- Identification of the *gas flow rate* demand of the main fluidized bed of the reactor as a function of temperature. For the given gas (argon) and particles (ilmenite with an average grain size of

150 µm), the best results were obtained for a constant gas velocity of 3.3 cm/s, corresponding to an inversely proportional gas mass inflow.

- Demonstration of *continuous particle feed* and discharge with active control of the solids flow rate. This was successfully achieved by careful and repeated adjustment of the standpipe gas feed in an active control loop.
- Operation of the reactor at a minimum mean *temperature* of at least 800°C, heated exclusively with concentrated solar energy. The best results were obtained operating at around 950°C. Local peak temperatures above 1000°C must be avoided to prevent possible sintering of the particles in the fluidized bed.
- Demonstration of *water production* from the chemical reaction of ilmenite with hydrogen. Several tests demonstrated water production above 100 ml/h. In particular, it could be demonstrated that the water separator designed by Ciemat-PSA was easily able to extract more than 90% of the produced water. As the remaining water is recycled into the reactor, finally no water is lost.
- Obtaining basic information on the *reaction kinetics*, the maximum possible velocity, and conversion of the reaction. The tests with a hydrogen share of about 8% in the feed gas obtained a 90-100% conversion. This corresponds to the thermodynamic optimum. It was interesting to see that the hydrogen conversion depends mainly on the water concentration in the product gas and not on the hydrogen concentration in the feed gas.

Figure 103. Oresol system in summer 2021 awaiting future testing. In the background the recently replaced, brand-new concentrator of the PSA Solar Furnace.

Due to the ongoing problems with the main particles filter mentioned in previous annual reports, tests could never be longer than 1.5 hours, and therefore these results are still preliminary. There is now a better filter available with a 20x increased filter area that hopefully allows for longer experiments. These tests are scheduled for November and December 2022.

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;
Inmaculada Cañadas, i.canadas@psa.es

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. Advance in the knowledge of the hydrogen production process via solar thermochemical water splitting at very high temperature.

2. Develop improved solar concentrating facilities for durability testing of materials for thermochemical applications.

3. Build up the necessary skills and training capacity in the partnering teams to continue working on this issue.

Achievements in 2021: The project has just begun in September 2021 and a kick-off meeting has been held at PSA in order to select the first bunch of materials to be thermally exposed as candidate ceramic substrates. Samples of these materials are about to be tested at PSA's SF-40 facility at the time of writing this report.

Bio-mimetic and phyto-technologies designed for low-cost purification and recycling of water, INDIA--H_2O

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

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

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

Background: INDIA-H20 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 2021: CIEMAT participated in the design of a conceptual model to monitor different process parameters of the batch reverse osmosis (BRO) and the forward osmosis (FO) unit. One of the schemes works over wireless connection (at PDPU) and the other one works over wired RS-232 support (at Lodhva village). Sub-modules used in the monitoring scheme have been developed. In addition, CIEMAT has used the models described in Deliverable D4.2 and the operation manual to test, in simulation, the operation of the BRO-FO system designed for PDPU location. The model assumptions used were: PV peak installed power 3.24 kW, batteries (2 kWh), and no grid connection. Finally, a preliminary definition of the energy management strategy has been completed. The objective is to minimize the cost of the water but assuring that we are supplying the water demanded by the school and halophytes.

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)

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

Funding agency: European Commission, INTERREG Atlantic Area Programme

Background: According to the priorities established 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 2021: The main activity during 2021 has been focused on the improvement of the simulation models aimed at the techno-economic evaluation of the combination of photovoltaic plants and central receiver solar thermal plants to feed reverse osmosis units. These improvements have focused on the management protocols of the thermal storage system as well as the operation of the reverse osmosis plant at partial load. During this year, work has also been carried out on the integration of forward osmosis technology as a pre-treatment for the MED process, obtaining theoretical results that show recovery ratio values of up to 55% while maintaining energy consumption values (GOR) above 13. Regarding the evaluation activity of the vacuum assisted membrane distillation technology, it has been carried out in batch configuration with the aim of increasing the recovery ratio and extending the application of the technology to other areas such as brine concentration and water mining.

Next generation water-smart management systems: large scale demonstrations for 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 FARM, MADISI

Contacts: 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. It considers water as a resource, a consumable and a durable good. To capture the full potential of the circular water economy, it proposes different strategies 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 be created as well.

Achievements in 2021: CIEMAT set up the demo plant at Plataforma Solar de Almería, consisting of a nanofiltration (NF) unit to pre-treat seawater before a multi-effect distillation (MED) plant powered by solar thermal energy. The NF eliminates the divalent salts from the seawater, allowing the MED plant to operate at higher temperatures and concentration, to reach higher thermal efficiency and salinity conditions near saturation. A further crystallizer should be able to obtain sodium chloride salts of greater purity from the MED brine in the absence of divalent ions. The reject from the NF, rich in divalent salts can be combined with the distillate produced by the MED plant for better value towards irrigation. The different systems have been implemented, including a large storage (300 m3) of real seawater with a chiller to dissipate the waste heat so that real seawater can be used and circulated through the systems. We also formed a Community of Practice of the case study to discuss barriers, identify required policies, assess sustainability issues and elaborate a preliminary market mapping. We organized a first meeting to discuss these matters and how to incorporate criteria based on value sensitive design in the implementation of the system.

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.

Contacts: 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 2021: Design of the solar membrane distillation pilot plant that will be implemented in CS2, comprising a plate and frame module with 4 effects in a multi-effect configuration using vacuum. Set-up of a laboratory system to test the different membranes that will be evaluated in the first phase of the project, including hollow fibre membranes which have never been tested before at PSA. Results so far do not improve on flat-sheet membranes.

Interdisciplinary 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 2021: Two project meetings have taken place virtually, both organized by the coordinators (University of Torino, Italy), and containing the update on the different technical and administrative and diffusion WPs. First meeting took place the 1st and 2nd March, 2021 and contained a technical WPs' update sessions with 15 minutes presentation of each one of ESR´s work carried out along the last part of their PhD. Second project meeting took place 6th and 7th of July, using the 6th for the presentation of a summary of ESR´s PhD Thesis content as it was considered as the final meeting before starting the official defence of each one of the PhD´s generated within the WPs of AQUALITY. Main Research activities carried out by the Solar Treatment of Water unit have 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 is performing his PhD.

One of the last works carried out by Dennis Deemter in the frame of AQUALITY project has been the creation of novel solar photocatalytic TiO2 washed Zirconia ultrafiltration membrane, in his secondment in Liqutech (partner of AQUALITY), for the retention of contaminants and with the potential ability of self-cleaning with natural solar radiation. This last property was demonstrated to be highly interesting to reduce maintenance issues on this kind of membranes provoked by the fouling (Figure 104). Last results of Ilaria Berruti in the frame of WP3 is related with the study of new photocatalysts efficiency, based on zinc oxide, for the simultaneous elimination of microcontaminants and pathogens from urban wastewater effluents. Different concentrations of ZnO-Ce have been tested in isotonic wastewater and urban wastewater (Figure 105). In addition, the 8th of July 2021, after the project meeting, FACSA and PSA organized an online workshop in the frame of the AQUALITY project focused on “Sustainable Technologies for Water Reuse”. For more details visit the website.

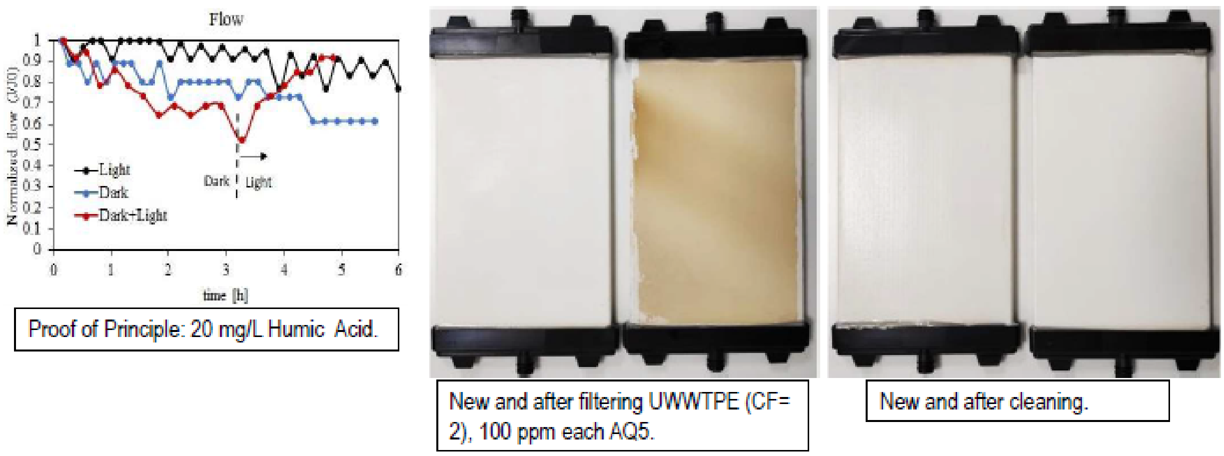
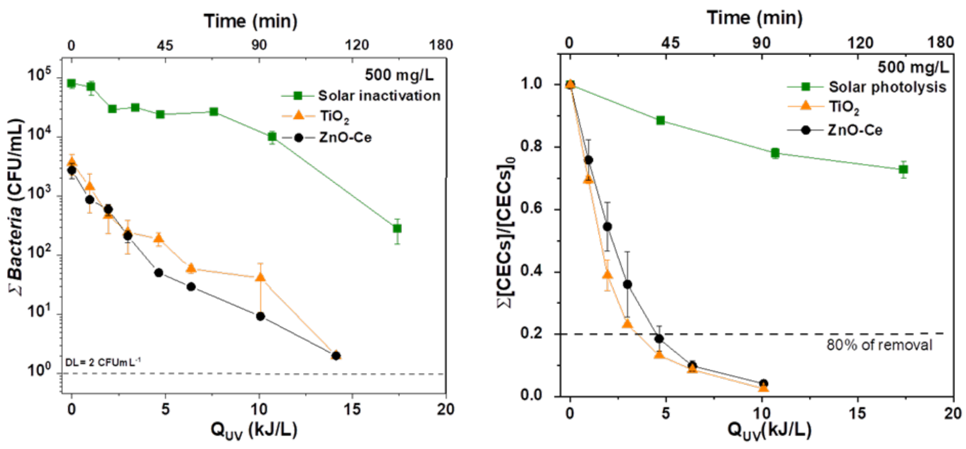


Figure 104. Assessment of a novel photocatalytic TiO_2 washed Zirconia ultrafiltration membrane for Humic Acid retention and self-cleaning potential under natural solar radiation



(a) (b)

Figure 105. Comparison of TiO_2, ZnO-Ce and mere solar radiation for (a) bacteria inactivation and (b) contaminants of emerging concern elimination.

Photo-irradiation and 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.

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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 Concerns (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 jerrycan for solar water disinfection, and (vi) a 2,000 L/day electrocoagulation, oxidation, and disinfection t system.

Achievements in 2020: Annual general assembly meeting of the PANIWATER project took place the 30th and 31st of March 2021 virtually. The progress on WP2 (wastewater treatment) was presented by Isabel Oller as the leader of the WP from the European side in coordination with the Indian part. In this meeting the definition of the intellectual property rights percentages to be assigned to each partner in each one of the activities and technologies defined and studied in the project has been carried out. In addition, final results obtained in WP2 by the Solar Treatment of Water Unit at PSA indicating the efficiency of UVC/50 mg/L H_2O_2 for the elimination of micropollutants and inactivation of pathogens in actual urban wastewater treatment plant effluents, were presented. Such technology was selected as the one to be implemented in a DEMO site in India in combination with PV for the electricity supply of the plant. The steering committee of the PANIWATER project took place 22nd and 23rd of September 2021, as an online event, too (Figure 106). In that meeting, the main issues related to the start-up of the MITOX technology based on the combination of advanced oxidation technologies for the elimination of contaminants of emerging concern and pathogens present in Indian urban wastewaters were discussed. It is important to highlight that an amendment process was initiated in 2020 and has finalized in 2021 in which, among other modifications mainly in deliverables final dates, the University of Almería (CIESOL and the “Analytical Chemistry” functional unit) has been added to the consortium as a third party of CIEMAT with the objective of better focussing on the accurate identification and quantification of microcontaminants and disinfection by-products actually present in Indian wastewaters as well as their proper monitoring along the oxidation processes proposed For more details visit the website.

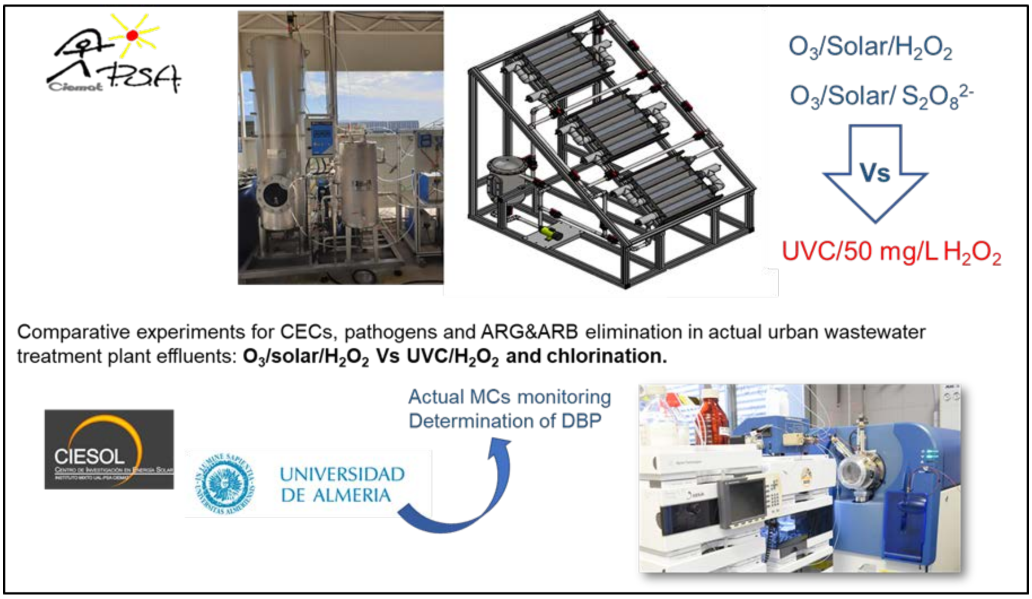


Figure 106. Summary of the experimentation to be carried out in the final period of PANIWATER by the Solar Treatment of Water Unit at PSA in collaboration with UAL-CIESOL.

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

Participants: UPV, URJC, CIEMAT.

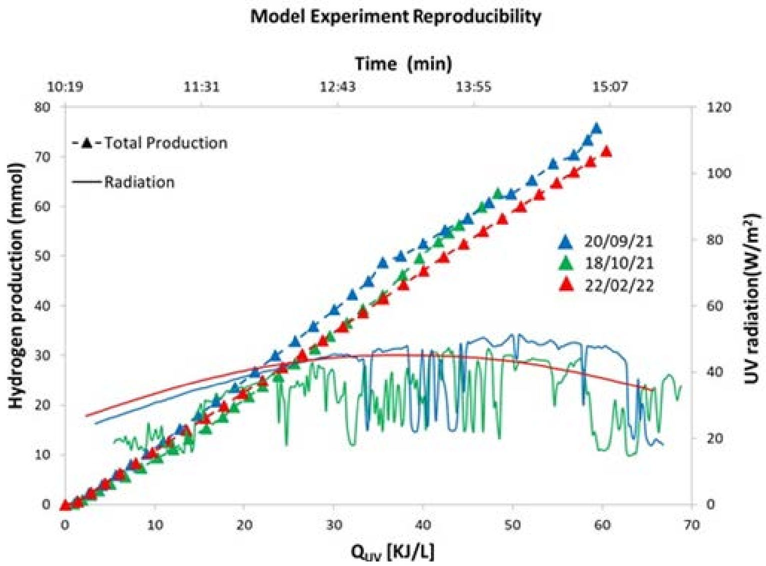
Contacts: Sixto Malato, sixto.malato@psa.es

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

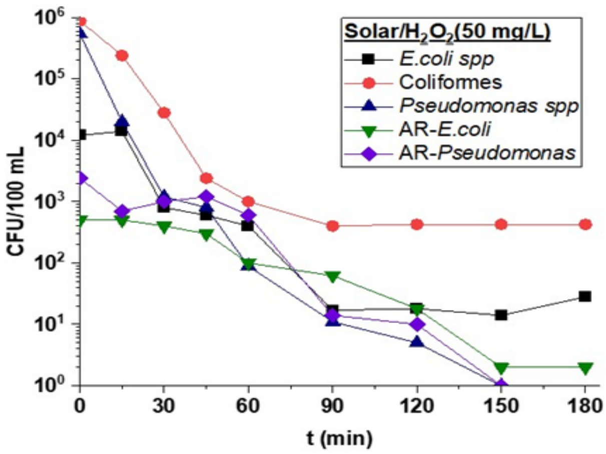
Background: The project tries to put together the know-how of in different areas of AOPs and wastewater decontamination to be a step forward to solve real problems of our society by the design of new strategies for the treatment of complex wastewaters, soil washing, or hydrogen generation adapted to 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 renewables 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 treatment (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 2021: Many different advances were already 100% accomplished and other attained during 2020 as an experimental campaign with different photocatalytic materials carried out with the aim of study the “solar-to-hydrogen” conversion efficiency (STH). The oxidative capability of different Advanced Oxidation Processes for antibiotics removal, antibiotic resistant (AR) bacteria inactivation and effect on AR genes was addressed. Combination/integration of advanced technologies for resource recovery (phosphorous, magnesium, potassium, ammonium, etc.) was also investigated. Mechanistic process kinetics and reactor modelling allowed the reliable prediction of the scaled-up processes in order to conduct their techno-economical evaluation. Treatment costs of advanced treatment for permitting 80% removal of CECs relative to the raw wastewater was assessed.



(a)



(b)

Figure 107. a) Photocatalytic H_2 generation during three consecutives 5 h tests with TiO_2-CuO (10:1) = 0.2 g L-1 and [Glycerol] = 0.05 M; b): Inactivation of E. coli spp, Coliforms, Pseudomonas spp, AR-E. coli and AR-Pseudomonas in WWTP effluent through solar/H_2O_2.

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

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

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M. Inmaculada Polo, inmaculada.polo@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 as 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 freshwater 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. And, not least, it operates on solar energy, ensuring a low cost of operation.

Achievements in 2021: Mid-term review meeting of AQUACYCLE has taken place virtually the 23rd and 24th of February 2021 within the motto "Building on what has been achieved to reach all of our targets". Mr. George Simos from the Managing Authority of European Territorial Cooperation Programmes attended the meeting. Main tasks implemented by the Solar Treatment of Water unit at PSA during the first 18 months of the project were presented in this meeting. In addition, the design of the raceway pond reactor for treating up to 5 m^3/day of the effluent coming from the vertical and horizontal wetlands in the municipal wastewater treatment plant of Blanca in Murcia (Spain) (Figure 108). The 22nd of June 2021, members of the Solar Treatment of Water unit visited the place where the raceway pond reactor must be constructed in the lower part of the horizontal wetland in the urban wastewater treatment plant of Blanca (operated by ESAMUR), Murcia. For more details visit the website.

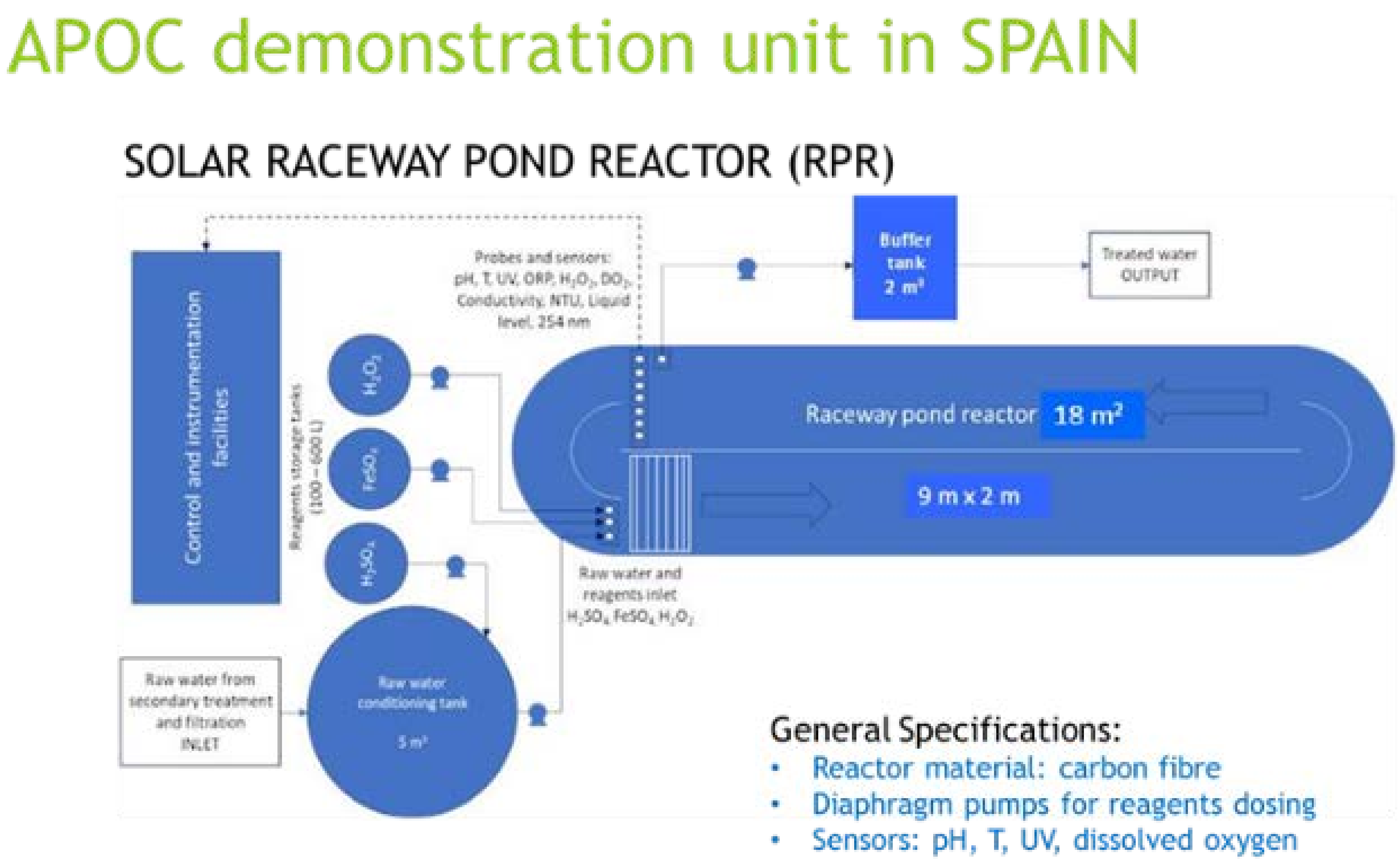

Figure 108. Preliminary design of the raceway pond reactor at DEMO scale to be installed in the Urban Wastewater Treatment Plant of Blanca in Murcia.

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.

Contact: Isabel Oller, isabel.oller@psa.es;
M. Inmaculada Polo, inmaculada.polo@psa.es

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 best treatment technologies based on high efficiency, low energy, low cost and low or null chemical and microbiological risks.

Objectives: NAVIA project aims at developing 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 2021: During this year, the activities carried out by CIEMAT have been focused on the assessment of several solar photocatalytic and photochemical treatments for water purification. Several novel photocatalytic and immobilized materials in different substrates developed by UPV partner were assessed for water disinfection and decontamination using *E. coli* and *E. faecalis* and Sulphametoxazole (SMX) as model of microbial and organic contaminants pollutants (Figure 109). A preliminary test carried out at laboratory scale in a solar simulator showed a good performance of GW_TiO_2 only for water decontamination (reaching an efficient degradation rate of SMX); while for disinfection, only GW_RB demonstrated to have a significant capability for successfully inactivate *E. faecalis*. More test related with the performance of the new materials are currently in progress.

On the other hand, the assessment of different solar photochemical treatments (such as H_2O_2, PAA, persulfate, and photo-Fenton with EDDS as iron quelate) at pilot plant scale in a solar CPC reactor with actual secondary effluents of UWW have been also carried out during this year. Several chemical (trimethoprim, Sulfamethoxazole and pyrimethanil) and microbiological targets (*E. coli,* coliforms and coliphages) were monitored along the different processes, as well as several ARGs (16S RNA, *Sul1*, *intl1*, *qnrS Tet(E)*, *blaTEM*). Results demonstrated the success capability of these treatments at pilot plant for UWW reclamation, and more analysis and experimental conditions will be investigating to optimize the process performance.

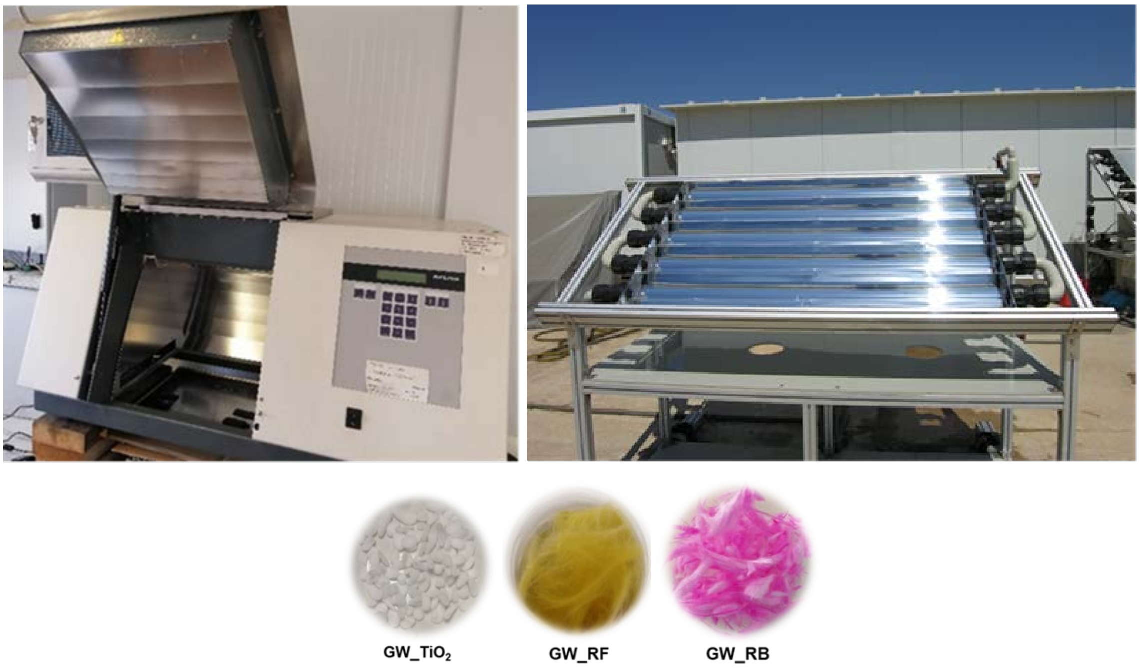

Figure 109. Images of the solar simulator SUNTEST XLS+ used for testing novel photocatalytic materials (left) and solar CPC photo-reactor used for UWW reclamation by solar photochemical treatment at pilot plant scale (right), both located at CIEMAT facilities. And several immobilized photocatalytic materials tested for water purification in the solar simulator (GW: glass wool; RF: Riboflavin; RB: Rose Bengal).

Solar catalysis for a renewable energy future, SOLFUTURE.

Participants: FUNDACION IMDEA ENERGIA, APRIA SYSTEMS, CEPSA, CSIC- ICMM, FUNDACIO INSTITUT CATALA DE INVESTIGACIO QUIMICA, CIEMAT.

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

Funding agency: R&D&i in strategic lines, in public-private collaboration, of the State Program of R&D&i Oriented to the Challenges of Society (Reference 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: On one hand, the development of photocatalytic technologies, based on the production of H_2 from wastewater and biomass as reductant using hybrid organic/inorganic heterojunctions based on metal oxides and conjugated porous polymers. On the other hand, a photo(electro)chemical cell will be design and built combining a hybrid photocathode, formed by organic-inorganic heterojunctions 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 2021: Significant advances in the photocatalytic H_2 production, CO_2 and N_2 reduction, as well as wastewater treatment, have been performed in the last years. However, they mainly focus on TRL ≤ 3 developments. Thus, it is necessary to tackle these technologies with a holistic approach to achieve progress in innovative CO_2 valorisation and N_2 fixation technologies. The key technological advancements will be focused on the development of novel materials with improved photocatalytic properties. Project has just begun on 1 December 2021.

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) (Grant Agreement Nº 101037428).

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 CO_2 emissions 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, 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 with the implementation of water treatment solar based solutions in two different countries, Madagascar and Sierra Leona.

Achievements in 2021: The kick-off meeting of the project took place last 1st November 2021 via on-line due to the pandemic situation. Therefore, activities carried out by CIEMAT along 2021 have been mainly focused on starting the approach of the potential low-cost solar photocatalytic water treatment to be implemented as renewable energy technology in Sierra Leona. It will be based on solar reactor designs which production could be easily transferred to an African partner, following any of the diagrams showed below (Figure 110). It will contain novel photocatalytic material immobilized provided by Tekniker to improve the efficiency of the solar treatment. A pilot plant reactor will be design and built by Arenys for a total volume of 50 L of water. And its efficiency under natural sunlight for removal/abatement of several microcontaminants and waterborne pathogens (*E. coli*, Coliforms, *Enterococcus faecalis* and antibiotic resistant bacteria) will be tested at CIEMAT-PSA facilities. Additionally, the eco-toxicity of the treated water (*Vibrio fisheri*) and the phytotoxicity (*Lactuta sativa*) will be also assessed.

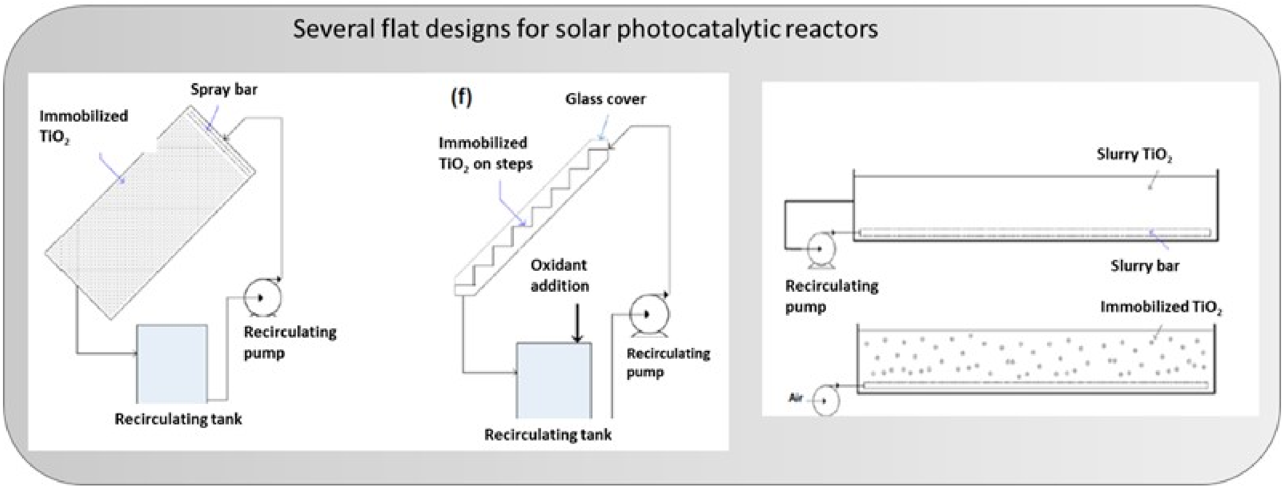

Figure 110. Different schematic designs for the solar photocatalytic reactors construction and further testing by CIEMAT-PSA.

Operation of two single layer panels prototype from SolarDew at the Plataforma Solar de Almeria.

Participants: CIEMAT (Plataforma Solar de Almería), SolarDew International B.V.

Contacts: Isabel Oller, isabel.oller@psa.es
Inmaculada Polo, inmaculada.polo@psa.es
Alba Ruiz-Aguirre, alba.ruiz@psa.es

Funding agency: Contract of service.

Background: SolarDew is planning to launch a pilot project of the SolarDew WaterStation in Chile and Australia. In preparation, prototype versions of the modules need to be evaluated on representative locations which will provide valuable input into the final design of the WaterStation. In order to evaluate the technology under representative climatological conditions, demonstrating the performance regarding productivity and water quality for the chosen application is needed.

Objectives: The objectives pursued with the evaluation of the mentioned prototype are: i) evaluation of the quality of the produced water; ii) determine if a re-contamination prevention for the storage tank is needed; iii) evaluation of production performance under local climatic and environmental conditions throughout the different seasons of the year; iv) evaluation of the supplied weather station to more standardized weather data; v) suggestions for further improvement to the design and operation of the product; vi) creation of a baseline case for both future tests and simulations in the lab.

Achievements in 2021: The commissioning of the SolarDew prototype (Figure 111) was carried out between 6th and 9th October 2020. The prototype was filled with simulated seawater at a concentration of sea salts of 35 g/L. Moreover, the monitoring of microbial presence in water was evaluated, firstly, with *Total Viable Count* (TVC) and secondly, with artificial contamination of feed solution with

Escherichia Coli (*E. coli*). Twice a week, the productions obtained from the two panels were measured as well as their quality. Moreover, data regarding temperatures and weather station were recorded at the end of the week. The system showed a good performance for 11 months (2.5 L/m^2/day), after that, panel replacement, purification bag or membrane, was required. The quality of the permeate production was excellent (conductivity below 5 µS/cm). According to microbial retention, results showed that the membranes did not retain the microorganisms, detecting *E. coli* in the permeate. Similarly, TVC analysis determined that the distillate contained an undesirable concentration of bacteria. To keep sterile conditions in an outdoor ambient was difficult, so the monitoring of TVC was influenced by the meteorology (wind, dust, etc). However, the presence of E. coli in the production, can only be due to its passage through the membrane. This event was unexpected and only through an autopsy of the system, an answer to what happened could be obtained. Anyway, to obtain microbiologically safe water, the use of a post-treatment would be required.

Figure 111. SolarDew prototype installed 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.

Contact: Alba Ruiz-Aguirre, alba.ruiz@psa.es

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 of 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 2021: The kick-off meeting of the project took place last 31st March 2021 through video conferencing. During the meeting, different strategies of coordination and collaboration were discussed by the two partners involved in the project to successfully accomplish the tasks of the project. The tasks carried out by PSA during this year have consisted in evaluating different strategies of pre-treatment of exhausted passivation baths contaminated with iron and zinc ions to remove these compounds before its treatment with membrane distillation to regenerate the passivation solution. The precipitation of zinc and iron at a pH of 5.5 by addition of NaOH was the chosen treatment. A removal of 26 % and 41 % of zinc and iron was reached respectively. A study of corrosion in artificial atmospheres-salt mist was carried out at the facilities of Electroniquel S.A. company showing a minimal weight loss (0.02 %) and an appearance of white corrosion after 96 h, being the same behaviour as the fresh passivation solution. Moreover, a study of the resistance of the membrane used on membrane distillation system to the passivation solution was carried out showing a good resistance to this type of solution. Next step consists of testing the membrane distillation pilot plant (Figure 112) installed at CIEMAT facilities for the treatment of the passivation solution to produce demineralized water and the regeneration of the waste solution.

Figure 112. Membrane distillation- crystallization pilot plant installed at CIEMAT facilities.

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 2021: The research conducted at the LECE Laboratory at PSA, also using stock data previously gathered here, delivered the following in 2021:

- Considering the occupant behaviour as one of the most relevant influences in the energy performance of buildings, and also one of the most relevant sources of the performance gap, a research work focused on measuring the occupancy patterns as a variable that could contribute to overcome these problems has been conducted (Journal of Building Engineering 2021, 40, 102676). The indoor air temperature, the relative humidity, the CO_2 concentration and the total electricity consumption measurements have been evaluated as occupancy indicators. The proposed approach has been applied to three rooms of the ARFRISOL in-use office building at PSA. These offices have different levels of occupancy and users with different habits. This research demonstrates the capability to obtain occupancy patterns from measuring the CO2 concentration and the total electricity consumption. The deviation between the occupancy patterns obtained from these variables and the reference schedule is under 10%, and it is lower for the rooms with larger occupancy rates.
- A Co-heating test has been conducted in the Single-zone building at the LECE Laboratory. Several key aspects of the application of this building energy performance assessment method under warm and sunny weather have been systematically analysed. Special attention has been paid to the incorporation of the solar radiation to the calculations and to different ways of modelling its effect from measured data. Additionally, the same building has been assessed using design information of the building according to the procedure stablished by the Spanish Technical Code. The results of both assessments have been compared and the performance gap has been identified. Further research will address the identified performance gap.

12 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.

Figure 113. Photo taken during the Board of Governmental Representatives meeting.

A number of relevant milestones have been achieved by EU-SOLARIS during past year 2021. A framework agreement has been signed in February 2021 between the Spanish Ministry of Science and Innovation (MSI) and CIEMAT to substantiate the support to and regulate the participation of Spain in EU-SOLARIS. Also, the consortium passed successfully a review hearing by the European Strategy Forum on Research Infrastructures (ESFRI) in April 2021. The objective of this project monitoring exercise is to check whether EU-SOLARIS reached the Implementation Phase as described in the Roadmap 2021 Guide. After this hearing, a new version of the ESFRI Roadmap has been issued by ESFRI on December 2021. In this updated version, EU-SOLARIS has been formally recognized as a 'Landmark' in the Energy domain (fully established research infrastructure which reached the Implementation Phase), leaving the former status of 'Project' (initiative under development).

On the other hand, the 'Step 2' request to recognize EU-SOLARIS as an ERIC by the European Commission was submitted to the EC's Directorate-General for Research and Innovation by the Spanish MSI in September 2021.

At the time of writing this text, an amended version of the statutes has been already re-submitted for its final approval by the EC and, most likely, EU-SOLARIS ERIC will have 'green light' to formally become an ERIC in the coming months. Meanwhile, the partners are setting up the governing bodies and developing all supporting documentation and corporate image tools of the ERIC.

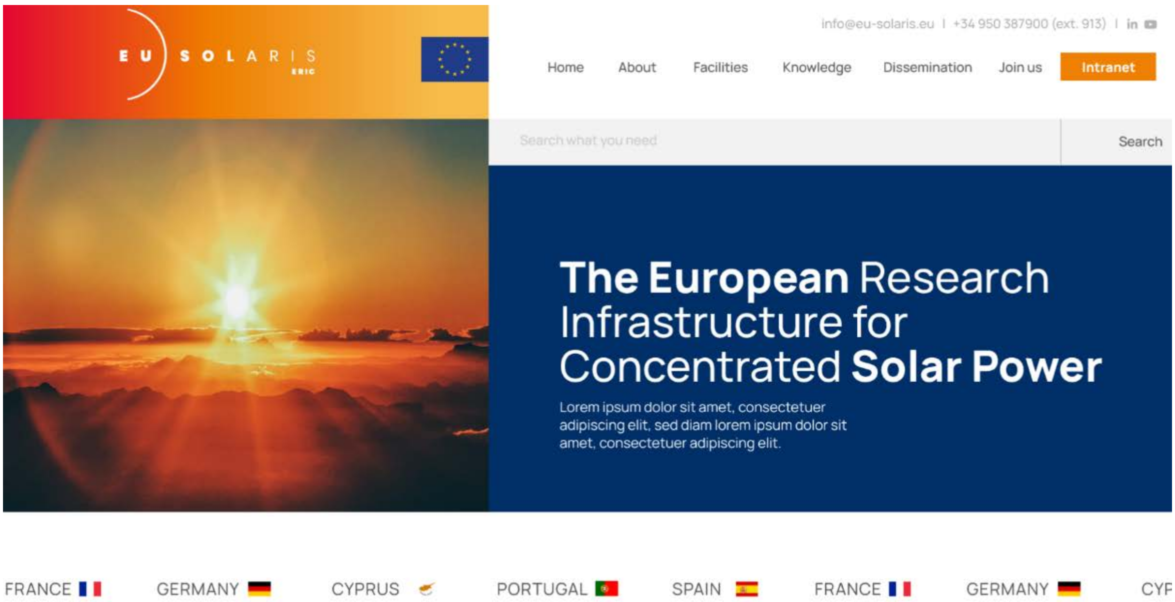

Figure 114. Image of the new website being developed for this EU-SOLARIS ERIC.

Contacts: Diego Martinez (dmartinez@psa.es)
Julián Blanco (jblanco@psa.es)

13 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 thirty 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, Carlos III of Madrid, Autónoma of Madrid, Santiago-Chile, Dalarna-Sweden, Salerno-Italy, etc)

The normal training and education activities provided by the PSA have continued to be affected by the outbreak of the COVID19 pandemic in early 2020. Despite these activities have been resumed gradually during 2021, some of them have been carried out virtually another year.

The close and enduring collaboration between CIEMAT and the University of Almería has allowed us to carry out the third 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.

Related with the Educational Cooperation Agreement between CIEMAT and the University of DALARNA (Sweden), the "Solar Thermal Power" course was given by PSA researchers in the framework of the Master Programme in Solar Energy Engineering. With 5 credits, this course takes part during the 2nd cycle of this Master Programme organized by the European Solar Engineering School, ESES (University of Dalarna). The first part of the CSP training course was hold from 20th October to 19th November and consisted of the theory lessons, while during the second part of the CSP training course the students from this university visited the facilities on 13th and 14th December. Due to COVID-19 pandemic, both parts were delivered virtually.

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 2nd SFERA summer school was held on 5th and 6th October 2021 in Almeria and it was focused on "Solar Heat for Industrial Processes (SHIP) and Solar Desalination". Afterward, Doctoral Colloquium was hosted at the same location on 7th and 9th October only for SFERA Members.

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.

14 Events

4th February 2021

Lecture

Lecture given by Sixto Malato, in the "Máster Universitario en gestion Sostenible y Tecnología del Agua" at the University of Alicante.

4th February 2021

Lecture

Lecture given by Sixto Malato, "La investigación en el tratamiento de regeneración de aguas: estado actual", in the Webinar "Gestión Sostenible del Agua en la Industria Agroalimentaria: Problemática y Retos de Futuro" organized by the University of Almería.

5th February 2021

Lecture

Lecture given by Maria Inmaculada Polo López, "Antibiotic Resistant Bacteria: ocurrence and removal from urban wastewater" in ODAKtr online seminar organized in the frame of SolarTwins project.

26th February 2021

Lecture

Lecture given by Isabel Oller Alberola ,"Water-Energy-Food nexus in industrial and urban wastewater recovery" in ODAKtr online seminar organized in the frame of SolarTwins project.

11th March 2021

Workshop

Loreto Valenzuela participates as guest speaker in the Workshop "Women in IES Initiative" celebrated virtually during the 22nd IEEE International Conference on Industrial Technology (IEEE ICIT2021).

12th March 2021

Lecture

Lecture given online by Isabel Oller, "Procesos solares avanzados de oxidación aplicados a la regeneración de aguas como acción frente al cambio climático" in the National School of electrochemistry in environmental processes (ENEPA 2021, Mexico).

16th March 2021

Lecture

Lecture given by Maria Inmaculada Polo López, "Water and wastewater disinfection by AOPs" in the International PhD School on Advanced Oxidation Processes (IPS-AOP) Online webinars series 2020-2021.

20th - 21st April 2021

Lecture

Lecture given by Rocío Bayón on "Materiales para aplicaciones solares" ("*Materials for solar applications*"), in the master course "Materiales Avanzados, Nanotecnología y Fotónica" ("*Advanced materials, Nanotechnology and Photonics*"), of the Universidad Autónoma de Madrid.

7th May 2021

Lecture

Lecture given by Esther Rojas on "Almacenamiento Térmico" ("*Thermal Energy Storage*"), in the course Especialista Almacenamiento Energético, organized by ITE and MOPEI Energía.

14th May – 4th June 2021

Lecture

Lecture given by Sixto Malato, “Proyectos de investigación. Concepción, desarrollo y redacción” in a formation activity organized by the University of Almería within “La vida más allá del doctorado: empleabilidad de un doctor en Ciencias”.

14th May – 4th June 2021

Lecture

Lecture given by Isabel Oller, “I+D+i en Organismos Públicos de Investigación (OPIS) e ICTS” in a formation activity organized by the University of Almería within “La vida más allá del doctorado: empleabilidad de un doctor en Ciencias”.

21st May 2021

Lecture

Lecture given by Sixto Malato, “Industrial wastewater treatment by solar AOPs and polishing urban wastewaters for irrigation” in the PHOTOWATER virtual workshop “Western Greece 2014-2020, MIS 5032954”.

25th May 2021

Lecture

Lecture given by Sixto Malato, “Fundamentos y tecnologías solares de oxidación avanzada” in the online seminar on solar treatment of water organized by ANID/REDES 180149 (Chile).

26th May 2021

Lecture

Lecture given by Maria Inmaculada Polo López, “Desinfección de agua y aguas residuales por Procesos Avanzados de OxidacióN”, in the online seminar on solar treatment of water organized by ANID/REDES 180149 (Chile).

26th May 2021

Lecture

Lecture given by Isabel Oller Alberola, “Tratamiento y valorización de aguas residuales industriales. Monitorización mediante técnicas analíticas y microbiológicas avanzadas” in the online seminar on solar treatment of water organized by ANID/REDES 180149 (Chile).

10th June 2021

Lecture

Participation of Guillermo Zaragoza in the webinar “Regando con agua cada vez más salina” organized by University of Almería and COEXPHAL.

22nd June 2021

Technical visit

Visit of ACCIONA and TEWER Engineering representatives to discuss joint R+D projects

24th September 2021

Dissemination Event

Participation of members of the Solar Treatment of Water Unit in “The Night of the European Scientists” in Allmería (Spain).

8th October 2021

Lecture

Participation of Eduardo Zarza as panellist in the event organized by the Colegio Oficial de Arquitectos de Almería about "Climate Change and Architecture".

21st October 2021

Lecture

Participation of Eduardo Zarza as panellist in the "CSP Technology Day" organized by the European project SOCRATCES within the Renewable Energy Week.

26th October 2021

Lecture

Participation of Guillermo Zaragoza as online panelist in the session "Decentralized solutions for securing safe water in the face of climate change" of the G-STIC Conference "Accelerating technological solutions for the SDGs", held in Dubai (UAE).

10th November 2021

Lecture

Participation of Esther Rojas as panellist and with the talk "Mix energético sostenible: desmitificando prejuicios" ("Sustainable energy mix: debunking prejudices"), in the 2021 Science and Innovation Week, Big Challenges: Energy workshop, organized by CIEMAT.

18th November 2021

Lecture

Participation of Esther Rojas as panellist and with the talk "Gestión masiva de energía a bajo coste: sistemas actuales de almacenamiento térmico" ("*Managing massive energy at low cost: current thermal energy storage systems*"), in the workshop of the fair GENERA 2021, entitled "Las centrales termosolares en el mercado eléctrico actual" ("*Thermosolar power plants in the current energy market*"), organized by SolarCONCENTRA, Protermosolar and CIEMAT.

18th November 2021

Lecture

Participation of Eduardo Zarza as panellist in the event "Jornada sobre Energía Termosolar" organized by CIEMAT, PROTERMOSOLAR and SOLARCONCENTRA, within the framework of GENERA-2021.

22nd November 2021

Lecture

Lecture given by Esther Rojas on "Almacenamiento Térmico" ("*Thermal Energy Storage*"), in the course Tecnologías, Operación y Aplicaciones del Almacenamiento de Energía en Sistemas Eléctricos organized by SECARTYS and CIEMAT.

23rd November 2021

Lecture

Participation of Guillermo Zaragoza as online guest speaker in the webinar "Desarrollo de tecnologías solares e integración multidisciplinaria de soluciones productivas a pequeña escala aplicadas a la macro zona Chile-Perú-Bolivia" organized by Solar Energy Research Center (Chile).

23rd November 2021

Lecture

Lecture given by Sixto Malato, “Regeneración de aguas mediante energía solar como vector de transformación del ciclo integral del agua” in the III Cultural Day “Una mirada a nuestra tierra” organized by the “Asociación de amigos del instituto laboral Fernando el Católico de Vera”, Almería (Spain).

25th – 26th November 2021

Lecture

Participation of Samira Nahim Granados and Sixto Malato in the VI Reunión Nacional de Grupos de Fotocatálisis, with the talk: “Fotocatálisis en la Plataforma Solar de Almería: últimos avances en regeneración de aguas y reenfoque de actividades de producción fotocatalítica de hidrógeno”. A Coruña (Spain).

25th November 2021

Lecture

Lecture given by Isabel Oller, “I+D+I en Tecnologías de oxidación avanzada para la desinfección y eliminación de contaminantes emergentes” in the XIII Jornadas sobre la Unión Europea. Innovación y retos de futuro en la depuración y regeneración de aguas residuales en la Unión Europea. Organized by Diputación de Almería and the University of Almería.

15 Publications

PhD Thesis

Marina Casanova Molina. “Medida de Alta Irradiancia en Centrales Solares Termoeléctricas de Receptor Central”. Universidad de Almería 2018-2021.

Gulnara Maniakova. “Tertiary treatment of urban wastewater by advanced oxidation processes”. University of Salerno (Italy). Supervisors: Prof. Luigi Rizzo and Prof. Sixto Malato

Elizângela Pinheiro da Costa. “Removal of contaminants of emerging concern and disinfection in secondary municipal wastewater by circumneutral solar photo-fenton in open reactor”. Federal University of Minas Gerais (UFMG), Brasil. Supervisors: Prof. Camila Amorim, Prof. Sixto Malato.

Iván Sciscenko. “Emerging Photochemical Processes Involving Iron for Wastewater Treatment”. Universidad Politécnica de Valencia, España. Supervisors: Prof. Dr. Antonio Arqués, Dr. Isabel Oller and Dr. Carlos Escudero.

Line-focus Concentrating Solar Thermal Technologies Unit

SCI PUBLICATIONS

Arias, I., Zarza, E., Valenzuela, L., Pérez-García, M., Alfonso, J, Escobar, R. 2021. Modelling and Hourly Time-Scale Characterization of the Main Energy Parameters of Parabolic-Trough Solar Thermal Power Plants Using a Simplified Quasi-Dynamic Model. ***Energies*** 14(1):221. DOI: 10.3390/en14010221.

Biencinto, M., Bayón, R., González, L., Christodoulaki, R., Rojas, E. Integration of a parabolic-trough solar field with solid-solid latent heat storage in an industrial process with different temperature levels. ***Applied Thermal Engineering*** 184 (2021):116263. DOI: 10.1016/j.applthermaleng.2020.116263.

Biencinto, M., Rojas, E., Bayón, R. Analysis of a hybrid dry cooling system for solar thermal electricity plants in deserts. ***Applied Thermal Engineering*** 186 (2021):116487. DOI: 10.1016/j.applthermaleng.2020.116487.

Sanda, A., Moya, S., Valenzuela, L., Cundapí, R. Three-dimensional thermal modelling and heat transfer analysis in the heat collector element of parabolic-trough solar collectors. ***Applied Thermal Engineering*** 189 (2021):116457. DOI: 10.1016/j.applthermaleng.2020.116457

Soares, J., Oliveira, A.C., Valenzuela, L. A dynamic model for once-though direct steam generation in linear focus solar collectors. ***Renewable Energy*** 163 (2021): 246-261. DOI: 10.1016/j.renene.2020.08.127

BOOKS CHAPTERS AND NOT SCI JOURNALS

Dominguez-Lopez, L.M., Valenzuela, L., Zarza, E. A new facility for testing line-focusing concentrating solar collectors for process heat applications. ***Proceeding of the ISES EuroSun2020 Conference - 13th***

International Conference on Solar Energy for Buildings and Industry. A. Charalambides, W. Streicher, D. Mugnier, Eds. ISBN: 978-9820408-2-0. DOI: 10.18086/eurosun.2020.08.02

PRESENTATIONS AT CONGRESSES

Plenary, keynotes and other Guest lectures

Valenzuela, L. "How Concentrated Solar Power (CSP) contributes to energy transition". ***IEEE ICIT 2021 - 22nd International Conference on Industrial Technology***, March 11th, 2021.WIE Workshop. Virtual, https://ieee-icit2021.org/

Zarza, E. "La experiencia con Centrales Termosolares. Descarbonización del sector eléctrico español". ***Sexta Jornada de Ciencia y Tecnología Aplicada***, 21-23 April 2021. Cuernavaca (Mexico)

Zarza, E. Invited panellist at the CSP Joint Webinar (https://socratces.eu/summary-of-the-csp-projects-joint-webinar/) organized by the European CSP projects SOCRATCES (https://socratces.eu/), MUSTEC (https://www.mustec.eu/), NEXTOWER (https://www.h2020-nextower.eu/) and SFERA-III (https://sfera3.sollab.eu/) and held on 25 June 2021

Zarza, E. Invited speaker at the ***Expert Workshop on "Energy Storage Systems"***, held on May 20th (https://www.world-petroleum.org/workshops/83-wpc-expert-workshops-2018-2020/448-energy-storage-systems

Zarza, E. "The Role of Concentrating Solar Thermal (CST) Systems in the decarbonization of the energy sector". Keynote presentation at the opening session of the ***International Conference on Renewable Energies and Power Quality (ICREPQ'21)***. Almeria 28 July 2021

Oral presentations

Alcalde-Morales, S., Valenzuela, L., Serrano-Aguilera, J.J. Numerical investigation of a trapezoidal cavity multi-tube receiver for a linear Fresnel collector. ***SolarPACES 2021***, September 27-October 1, 2021. Online Event.

Biencinto, M., González, L., Valenzuela, L. Simulation and economic analysis of an innovative compact linear Fresnel collector coupled to two industrial processes with low and medium temperatures. ***SolarPACES 2021***, September 27-October 1, 2021. Online Event.

Saliou, G., Hilgert, C., López-Martín, R. Segregation of influences on flexible pipe connectors (REPA) force under field operation condition for parabolic trough collector plants. ***SolarPACES 2021***, September 27-October 1, 2021. Online Event.

Posters

García, G., Egea, A., Valenzuela, L., Pulido, D., Liria, J. Advanced sun-tracking control for an innovative linear Fresnel collector. ***SolarPACES 2021***, September 27-October 1, 2021. Online Event.

Point-Focus Solar Thermal Technologies Unit

SCI PUBLICATIONS

Barbero F.J., López G., Ballestrín J., Bosch J.L., Alonso-Montesinos J., Carra M.E., Marzo A., Polo J., Fernández-Reche J., Batlles F.J., Enrique R. Comparison and analysis of two measurement systems of horizontal atmospheric extinction of solar radiation. ***Atmospheric Environment.*** 261 (2021) 118608. DOI: 10.1016/j.atmosenv.2021.118608

Alonso-Montesinos J., Ballestrín J., López G., Carra E., Polo J., Marzo A., Barbero J., Batlles F.J. The use of ANN and conventional solar-plant meteorological variables to estimate atmospheric horizontal extinction. ***Journal of Cleaner Production*** 285 (2021) 125395. DOI: 10.1016/j.jclepro.2020.125395

Marzo A., Salmon A., Polo J., Ballestrín J., Soto G., Quiñones G., Alonso-Montesinos J., Carra E., Ibarra M., Cardemil J., Fuentealba E., Escobar R. Solar extinction map in Chile for applications in solar power tower plants, comparison with other places from sunbelt and impact on LCOE. ***Renewable Energy*** 170 (2021) 197-211. DOI: 10.1016/j.renene.2021.01.126.

Marzo A., Ballestrín J., Alonso-Montesinos J., Ferrada P., Polo J., López G., Barbero J. Field Quality Control of Spectral Solar Irradiance Measurements by Comparison with Broadband Measurements. ***Sustainability*** 13 (2021) 10585. DOI: 10.3390/su131910585.

Carra M.E., Ballestrin J., Barbero J. Atmospheric extinction of solar radiation measurement in solar thermal electric plants. *Optica Pura y Aplicada*. 17 (2021) 1 - 11. DOI: 10.7149/OPA.54.2.51054

Shohoji N., Oliveira F.A.C., Galindo J., Rodríguez J., Cañadas I., Fernandes J.C., Rosa L.G. Synthesis of non-cubic nitride phases of va-group metals (V, nb, and ta) from metal powders in stream of nh3 gas under concentrated solar radiation. ***ChemEngineering*** 5 (2021) 19. DOI: 10.3390/chemengineering5020019

PRESENTATIONS AT CONGRESSES

Oral presentations

Sanchez-Señorán D., Reyes-Belmonte M.A., Fernandez-Reche J., Avila-Marin, A. Numerical Simulation of Convective Heat Transfer Coefficient in Wire Mesh Absorbers with 0.1 mm Wire Diameter. 27th SolarPACES Conference (Online Event). September 26 - September 30, 2021.

Zaversky F., Fernández-Reche J., Casanova M., Monterreal R., Enrique R., Ávila-Marín A., Martínez S., Schmitz M., Castellanos A., Mallo R., Herrero S., López S., Mesonero I., Pérez I., McGuire J., Berard F. Experimental Testing of a 300 kWth Open Volumetric Air Receiver (OVAR) Coupled with a Small-Scale Brayton Cycle. Operating Experience and Lessons Learnt. 27th SolarPACES Conference (Online Event). September 26 - September 30, 2021.

Marzo A., Salmon A., Polo J., Ballestrín J., Alonso Montesinos J., Fuentealba E. Assessment of the Atmospheric Extinction for Solar Tower Power Plants along the Sun Belt: Preliminary Results. Solar World Congress (Virtual Conference), October 25 - October 29, 2021.

Sanchez-Señoran D., Reyes-Belmonte M.A., Fernandez-Reche J., Avila-Marin, Numerical simulation of Convective Heat Transfer Coefficient in 3D Wire Mesh Absorbers. Proceedings of the SolLab Doctoral Colloquium, Almería, Spain. October 7 – October 9, 2021.

Estremera N., Fernandez-Reche J., Rodriguez J. Characterization of the optical and thermal properties of materials exposed to high concentrated solar radiation. Proceedings of the SolLab Doctoral Colloquium, Almería, Spain. October 7 – October 9, 2021.

Posters

Avila-Marin A., Fernandez-Reche J., Carra M.E., Sanchez-Señoran D. CFD performance analysis of the volumetric absorber assembly within a standard cup. 27th SolarPACES Conference (Online Event). September 26 – September 30, 2021.

Sanchez-Señoran D., Reyes-Belmonte M.A., Fernandez-Reche J., Avila-Marin, A. Numerical Simulation of Convective Heat Transfer Coefficient in Wire Mesh Absorbers. Solar World Congress (Virtual Conference), October 25 – October 29, 2021.

Sanchez-Señoran D., Reyes-Belmonte M.A., Fernandez-Reche J., Avila-Marin, A. Numerical Simulation of Convective Heat Transfer Coefficient in Wire Mesh Absorbers with 0.1 mm Wire Diameter. 1st AERA (Avances en Energías Renovables y sus Aplicaciones en la Ingeniería) Conference, Madrid. October 14 – October 15, 2021.

Thermal Energy Storage for Concentrating Solar Thermal Technologies Unit

SCI PUBLICATIONS

Biencinto, M., Bayón, R., González, L., Christodoulaki, R., Rojas, E. Integration of a parabolic-trough solar field with solid-solid latent heat storage in an industrial process with different temperature levels. *Applied Thermal Engineering* 184 (2021):116263. https://doi.org/10.1016/j.applthermaleng.2020.116263

Biencinto, M., Rojas, E., Bayón, R. Analysis of a hybrid dry cooling system for solar thermal electricity plants in deserts. *Applied Thermal Engineering* 186 (2021):116487. DOI: https://doi.org/10.1016/j.applthermaleng.2020.116487

PRESENTATIONS AT CONGRESSES

Oral presentations

R. Bayón, V, Gismera, E. Rojas, Validation of lauric acid as PCM: study of thermal degradation under quasi-real working conditions, Enerstock 2021, Online 9-11 June 2021, Organizer Ljubljana University (Slovenia).

M.Rodríguez-García, R. Bayón, E. Alonso, E.Rojas, Experimental and theoretical investigation on using microwaves for storing electricity in a thermal energy storage medium, SolarPACES 2021, Online 27/9/2021 – 01/10/2021, Organizer: SolarPACES TCP.

E. Alonso E.r Rojas, A Simply Method to Determine the Thermal Capacity of Filler for Sensible Thermal Storage under Operating Conditions, SolarPACES 2021, Online 27/9/2021 - 01/10/2021, Organizer: SolarPACES TCP.

Materials for Concentrating Solar Thermal Technologies Unit

SCI PUBLICATIONS

García-Segura A, Sutter, F, Martínez-Arcos L, Reche-Navarro TJ, Wiesinger F, Wette J, Buendía-Martínez F, Fernández-García A. Degradation types of reflector materials used in concentrating solar thermal systems. Renew Sustain Energy Rev. 2021, 143, 110879. DOI: 10.1016/j.rser.2021.110879.

Buendía-Martínez F, Sutter F, Wette J, Valenzuela L, Fernández-García A. Lifetime prediction model of reflector materials for concentrating solar thermal energies in corrosive environments. Sol Energy Mater Sol Cells. 2021, 224, 110996. DOI: 10.1016/j.solmat.2021.110996.

Wiesinger F, Sutter F, Fernández-García A, Wette J, Hanrieder N. Sandstorm erosion on solar reflectors: A field study on height and orientation dependence. Energy. 2021, 217, 119351. DOI: 10.1016/j.energy.2020.119351.

Cañadas, I., Candelario, V.M., De Aloysio, G., Fernández, J., Laghi, L, Cuesta-López, S., Chen, Y., Marrow, T.J., Rinalde, A., Mariblanca Sánchez, A., Tatì, A., Testani, C. Characterization of solar-aged porous silicon carbide for concentrated solar power receivers. Materials. 2021, 14(16), 4627. DOI: 10.3390/ma14164627.

Shohoji, N., Costa Oliveira F.A., Galindo, J., Rodríguez, J., Cañadas, I., Cruz Fernandes, J., Guerra Rosa, L. Synthesis of Non-Cubic Nitride Phases of Va-Group Metals (V, Nb, and Ta) from Metal Powders in Stream of NH3 Gas under Concentrated Solar Radiation. ChemEngineering 2021, 5(2), 19. DOI: 10.3390/chemengineering5020019.

PRESENTATIONS AT CONGRESSES

Oral presentations

Wette, J. Fernández-García, A., Sutter, F., Wiesinger, F. In field Analysis of Microscopic Degradation of Solar Reflectors. SolarPACES 2021, September 27-October 1, 2021. Online Event.

Wette, J. Development of a methodology to study the degradation of solar field reflectors of concentrating solar thermal systems. 15th SolLab 2nd SFERA III Doctoral Colloquium, October 6 - 9, 2021. Almería (Spain).

García-Segura, A., Fernández-García, A.,Sutter, F., Ariza, M.J., Valenzuela, L. Impact of industrial environments on solar reflectors performance. SolarPACES 2021, September 27-October 1, 2021. Online Event.

Sánchez-Moreno, R., Buendía-Martínez, F., Fernández-García, A., Wette, J., Sutter, F. Degradation of Primary Mirrors under Accelerating Aging Tests. SolarPACES 2021, September 27-October 1, 2021. Online Event.

Wiesinger, F., Sutter, F., Fernández-García, A., Wolfertstetter, F. Identification of Soiling Properties for Different Minerals on Solar Mirrors via Artificial Soiling Setup. SolarPACES 2021, September 27-October 1, 2021. Online Event.

Posters

Wette, J., Fernández-García, A., Sutter, F., Attout, A. Novel Durable Anti-Soiling Coatings under Outdoor Conditions. SolarPACES 2021, September 27-October 1, 2021. Online Event.

San Vicente, G., Farchado, M., Germán, N., Morales, A., Santamaria, P., Fernández-García, A. Improved Abrasion Resistance of Antireflective Coatings on Glass Tube with a Hydrophobic Antisoiling Treatment. SolarPACES 2021, September 27-October 1, 2021. Online Event.

Thermochemical Processes for Hydrogen and Feedstock Production Unit

PRESENTATIONS AT CONGRESSES

Oral presentations

Vidal A.; Martínez D. An ageing protocol for testing high temperature solar materials for thermochemical applications SolarPACES 2021, September 27-October 1, 2021. Online Event.

Solar Thermal Applications Unit

SCI PUBLICATIONS

Abdel-Karim, A., S. Leaper, C. Skuse, G. Zaragoza, M. Gryta, P. Gorgojo. Membrane cleaning and pre-treatments in membrane distillation – a review. *Chemical Engineering Journal* 422, 129696, 2021. DOI: 10.1016/j.cej.2021.129696

Ayou D.S., G. Zaragoza, A. Coronas. Small-Scale Renewable Poly-generation System for Off-Grid Applications: Desalination, Power Generation and Space Cooling. *Applied Thermal Engineering*, 182, 116112, 2021. DOI: 10.1016/j.applthermaleng.2020.115835

Mata-Torres, C., P. Palenzuela, D.-C. Alarcón-Padilla, A. Zurita, J.M. Cardemil, R.A. Escobar. Multi-objective optimization of a Concentrating Solar Power + Photovoltaic + Multi-Effect Distillation plant: Understanding the impact of the solar irradiation and the plant location. *Energy Conversion and Management:: X* 11 (2021) 100088. DOI: 10.1016/j.ecmx.2021.100088

Poblete, R., Cortés, E., Pérez, N., Valdivia, M., Maldonado, M.I. Removal of organic matter from wastewater coming from fruit juice production using solar photo-Fenton process. *International Journal of Chemical Reactor Engineering*, 2021, 19(8), pp. 809-815

Ramos J., Gil J. D., Roca L., Rodriguez F., Berenguel M. Optimal Water Management in Agro-Industrial Districts: An Energy Hub's Case Study in the Southeast of Spain. *Processes*. 9 - 2, pp. 333. 2021. ISSN 2227-9717. DOI: 10.3390/pr9020333

Thomas, N., J. Swaminathan, G. Zaragoza, R.K. Abu Al-Rub, J.H. Lienhard V, and H.A. Arafat. Comparative assessment of the effects of 3D printed feed spacers on process performance in MD systems. ***Desalination***, 503, 114940, 2021. DOI: 10.1016/j.desal.2021.114940

Toledo-Camacho, S.Y.; Rey, A., Maldonado, M.I.; Llorca, J.; Contreras, S.; Medina, F. Photocatalytic hydrogen production from water-methanol and -glycerol mixtures using Pd/TiO2(-WO3) catalysts and validation in a solar pilot plant. ***International Journal of Hydrogen Energy***, 2021, 46(73), pp. 36152-36166. DOI: 10.1016/j.ijhydene.2021.08.141

BOOKS CHAPTERS AND NOT SCI JOURNALS

Palenzuela, P., J.A. Andrés-Mañas, B. Ortega-Delgado, G. Zaragoza. Solvent Extraction Regeneration Technologies. In Salinity Gradient Heat Engines. Elsevier, 1-40, ISBN 9780081028476, 2021

PRESENTATIONS AT CONGRESSES

Plenary, keynotes and other Guest lectures

G. Zaragoza. Opportunities for solar desalination with membrane distillation. International Conference of Water and Energy ICWE-21. 25-26 mayo 2021. Chlef (Argelia)

Oral presentations

Ortega-Delgado, B., Palenzuela P., Altae, A. Alarcón-Padilla, D.C, Zaragoza, G. Assessment of the potential of forward osmosis as pre-treatment of the multi-effect distillation process. 16th SDEWES Conference on sustainable development of energy, water and environment systems. October 10-15, 2021.

Palenzuela, P., Alarcón-Padilla, D.C., Ortega-Delgado, B., Zaragoza, G. Comparative assessment of multi-effect distillation and reverse osmosis processes coupled to solar-driven high-temperature power cycles. International Conference on Poly-generation ICP 2021, 04-06 October, 2021.

Requena, I., J. A. Andrés-Mañas, G. Zaragoza. Towards the operation of solar membrane distillation systems in batch for concentration of brines. 15th SolLab and 2nd SFERA III-Doctoral Colloquium. Almería, España, 2021.

Solar Treatment of Water Unit

SCI PUBLICATIONS

Polo-López M.I., Sánchez Pérez J.A. (2021). Perspectives of the solar photo-Fenton process against the spreading of pathogens, antibiotic resistant bacteria and genes in the environment. ***Current Opinion in Green and Sustainable Chemistry***, 27, 100416. DOI: 10.1016/j.cogsc.2020.100416.

Salmerón I., Sharma P.K., Polo-López M.I., Tolosana A., McMichael S., Oller I., Byrne J.A., Fernández-Ibáñez P. (2021). Electrochemically assisted photocatalysis for the simultaneous

degradation of organic micro-contaminants and inactivation of microorganisms in water. ***Process Safety and Environmental Protection*** 147, 488-496. DOI: 10.1016/j.psep.2020.09.060

Maniakova G., Salmerón I., Polo-López M.I., Oller I., Rizzo L., Malato S. (2021). Simultaneous removal of contaminants of emerging concern and pathogens from urban wastewater by homogeneous solar driven advanced oxidation processes. ***Science of the Total Environment*** 766, 144320. DOI: 10.1016/j.scitotenv.2020.144320.

Berruti I., Oller I., Polo-López M.I. (2021). Direct oxidation of peroxymonosulfate under natural solar radiation: Accelerating the simultaneous removal of organic contaminants and pathogens from water. ***Chemosphere*** 279, 130555. DOI: 10.1016/j.chemosphere.2021.130555

Ozores Diez P., Polo-López M.I., Martínez-García A., Waso M., Reyneke B., Khan W., McGuigan K.G., Fernández-Ibáñez P., Devery R., Quilty B. (2021). In vitro toxicity studies of novel solar water disinfection reactors using the E-screen bioassay and the Ames test. ***H2Open Journal*** 1, 204. DOI: 10.2166/h2oj.2021.108.

Berruti I., Nahim-Granados S., Abeledo-Lameiro M.J., Oller I., Polo-López M.I. (2021). UV-C Peroxymonosulfate Activation for Wastewater Regeneration: Simultaneous Inactivation of Pathogens and Degradation of Contaminants of Emerging Concern. ***Molecules*** 26, 4890. DOI: 10.3390/molecules26164890

Maniakova G., Salmerón I., Nahim-Granados S., Malato S., Oller I., Rizzo L., Polo-López M.I. (2021). Sunlight advanced oxidation processes vs ozonation for wastewater disinfection and safe reclamation. ***Science of the Total Environment,*** 787, 147531. DOI: 10.1016/j.scitotenv.2021.147531

Nahim-Granados S., Martínez-Piernas A.B., Rivas-Ibáñez G., Plaza-Bolaños P., Oller I., Malato S., Sánchez Pérez J.A., Agüera A., Polo-López M.I. (2021). Solar processes and ozonation for fresh-cut wastewater reclamation and reuse: Assessment of chemical, microbiological and chlorosis risks of raw-eaten crops. ***Water Research*** 203, 117532. DOI: 10.1016/j.watres.2021.117532

Ruiz-Aguirre A., López J., Gueccia R., Randazzo S., Cipollina A., Cortina J.L., Micale G. (2021). Diffusion dialysis for the treatment of H_2SO_4-$CuSO_4$ solutions from electroplating plants: Ions membrane transport characterization and modelling. ***Separation and Purification Technology*** 266, 118215. DOI: 10.1016/j.seppur.2020.118215

Yu X., Cabrera-Reina A., Graells M., Miralles-Cuevas S., Pérez-Moya M. (2021). Towards an efficient generalization of the online dosage of hydrogen peroxide in photo-Fenton process to treat industrial wastewater. ***Int. J. Env. Res. Public Health*** 18, 13313. DOI: 10.3390/ijerph182413313

Luna-Sanguino G., Ruíz-Delgado A., Duran-Valle C.J., Malato S., Faraldos M., Bahamonde A. (2021). Impact of water matrix and oxidant agent on the solar assisted photo-degradation of a complex mix of pesticides over titania-reduced graphene oxide nanocomposites. ***Catalysis Today*** 380, 114-124. DOI: 10.1016/j.cattod.2021.03.022

Costa E.P, Roccamante M., Plaza-Bolaños P., Oller I., Agüera A., Amorim C.C., Malato S. (2021). Aluminized surface to improve solar light absorption in open reactors: Application for micro-pollutants removal in effluents from municipal wastewater treatment plants. ***Science of the Total Environment*** 755, 142624. DOI: 10.1016/j.scitotenv.2020.142624

Salmerón I., Rivas G., Oller I., Martínez-Piernas A., Agüera A., Malato S. (2021). Nano-filtration retentate treatment from urban wastewater secondary effluent by solar electrochemical oxidation processes. ***Separation and Purification Technology*** 254, 117614. DOI: 10.1016/j.seppur.2020.117614

Kowalska K., Roccamante M., Cabrera Reina A., Plaza-Bolaños P., Oller I., Malato S. (2021). Pilot-scale removal of micro-contaminants by solar-driven photo-Fenton in treated municipal effluents: Selection of operating variables based on lab-scale experiments. ***J. Environmental Chemical Engineering*** 9, 104788. DOI:10.1016/j.jece.2020.104788

Deemter D., Oller I., Amat A.M., Malato S. (2021). Effect of salinity on pre-concentration of contaminants of emerging concern by nano-filtration: Application of solar photo-Fenton as a tertiary treatment. ***Science of the Total Environment*** 756, 143593. doi: 10.1016/j.scitotenv.2020.143593

Oller I., Malato S. (2021). Photo-Fenton applied to the removal of pharmaceutical and other pollutants of emerging concern. ***Current Opinion in Green and Sustainable Chemistry*** 29, 100458. DOI: 10.1016/j.cogsc.2021.100458

Salmerón I., Oller I., Plakas K.V., Malato S. (2021). Carbon-based cathodes degradation during electro-Fenton treatment at pilot scale: Changes in H_2O_2 electro-generation. ***Chemosphere*** 275, 129962. DOI: 10.1016/j.chemosphere.2021.129962

Salmerón I., Oller I., Malato S. (2021). Solar photo-assisted electrochemical processes applied to actual industrial and urban wastewaters: A practical approach based on recent literature. ***Chemosphere*** 279, 130560. DOI: 10.1016/j.chemosphere.2021.130560

Sciscenko I., Arqués A., Escudero-Oñate C., Roccamante M., Ruiz-Delgado A., Miralles-Cuevas S., Malato S., Oller I. (2021). A Rational Analysis on Key Parameters Ruling Zerovalent Iron-Based Treatment Trains: Towards the Separation of Reductive from Oxidative Phases. ***Nanomaterials*** 11, 2948. 10.1016/j.chemosphere.2021.130560

Soriano-Molina P., Miralles-Cuevas S., Oller I., García Sánchez J.L., Sánchez Pérez J.A. (2021). Contribution of temperature and photon absorption on solar photo-Fenton mediated by Fe^{3+}-NTA for CEC removal in municipal wastewater. ***Applied Catalysis B: Environmental*** 294, 120251. DOI: 10.1016/j.apcatb.2021.120251

Sciscenko I., Mestre S., Climent J., Valero F., Escudero-Oñate C., Oller I., Arqués A. (2021). Magnetic Photocatalyst for Wastewater Tertiary Treatment at Pilot Plant Scale: Disinfection and Enrofloxacin Abatement. ***Water*** 13, 329. DOI: 10.3390/w13030329

Cuervo Lumbaque E., Cardoso R.M., de Araújo Gomes A., Malato S., Sánchez Pérez J.A., Sirtori C. (2021). Removal of pharmaceuticals in hospital wastewater by solar photo-Fenton with Fe^{3+}-EDDS using a pilot raceway pond reactor: Transformation products and in silico toxicity assessment. ***Microchemical Journal*** 164,106014. DOI: 10.1016/j.microc.2021.106014

Bortot Coelho F.E., Deemter D., Candelario V.M., Boffa V., Malato S., Magnacca G. (2021). Development of a photocatalytic zirconia-titania ultrafiltration membrane with anti-fouling and self-cleaning properties. ***J. Environ. Chem. Eng.*** 9, 106671. DOI: 10.1016/j.jece.2021.106671

BOOKS CHAPTERS AND NOT SCI JOURNALS

Malato S., Oller I., Polo-López M.I.,Fernández-Ibañez P. (2021). Solar Detoxification and Disinfection of Water. In: Encyclopedia of Sustainability Science and Technology, R. A. Meyers (ed.). Springer, New York, NY. DOI: 10.1007/978-1-4939-2493-6_686-3.

PRESENTATIONS AT CONGRESS

Plenary, keynotes and other Guest lectures

Malato S. Procesos de oxidación avanzada para tratamiento de aguas contaminadas: conceptos generales, combinación con procesos de membrana y su aplicación para reutilizar el agua en agricultura. 4º Congreso Colombiano de Procesos Avanzados de Oxidación. Universidad Antonio Nariño (Colombia), 14 -16 de abril de 2021. Plenary.

Malato S. Solar photocatalytic hydrogen production at pilot scale. Challenges and opportunities in materials for green energy production and conversion. LE STUDIUM CONFERENCES. Loire Valley Institute for Advanced Studies (France), 15 - 17 June 2021. Invited speaker. Online event.

Oral presentations

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