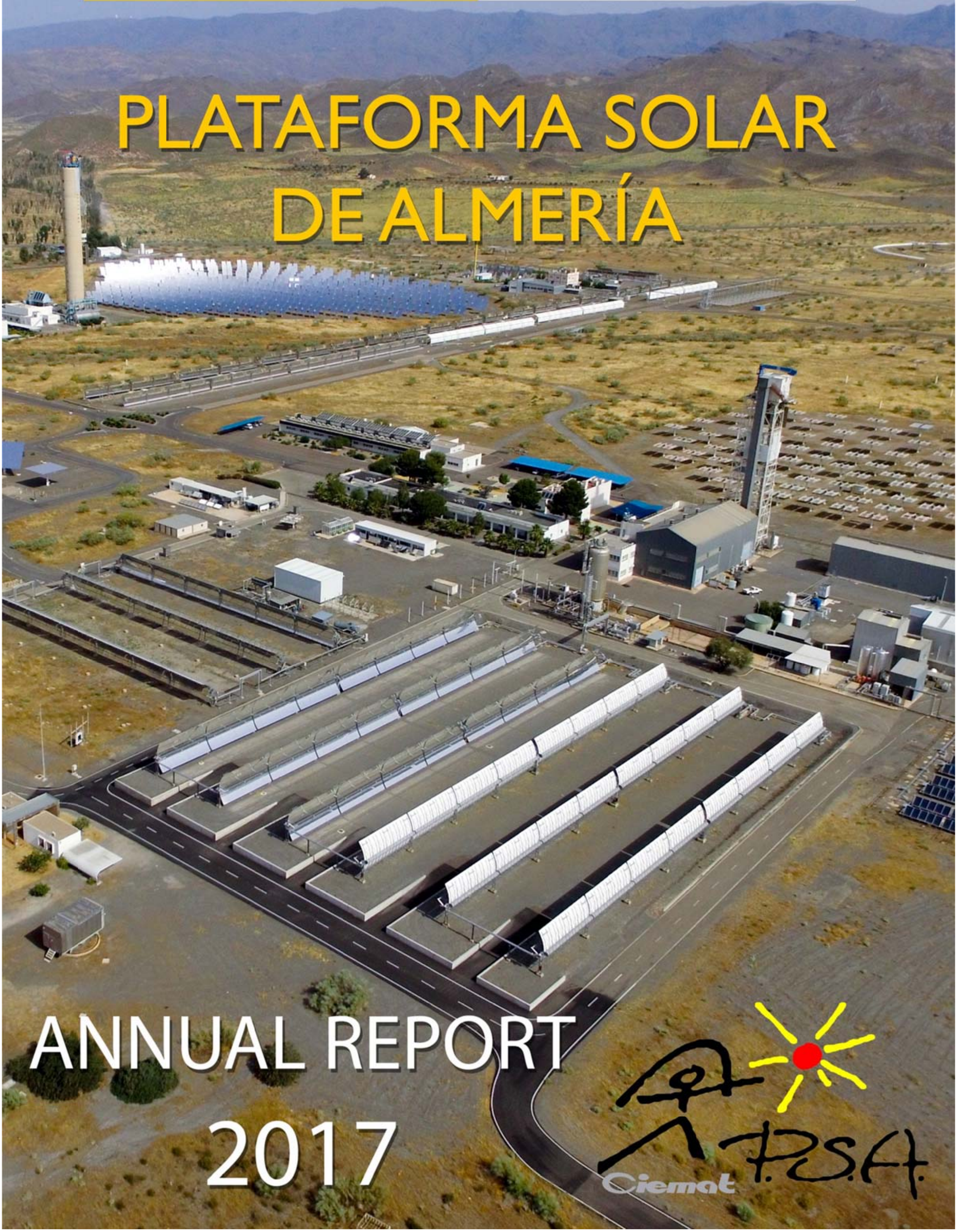
GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

PLATAFORMA SOLAR DE ALMERÍA



ANNUAL REPORT 2017

P.S.A. Ciemat

ANNUAL REPORT 2017

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1. GENERAL PRESENTATION

The Plataforma Solar de Almería (PSA), a dependency 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 Energy Department.

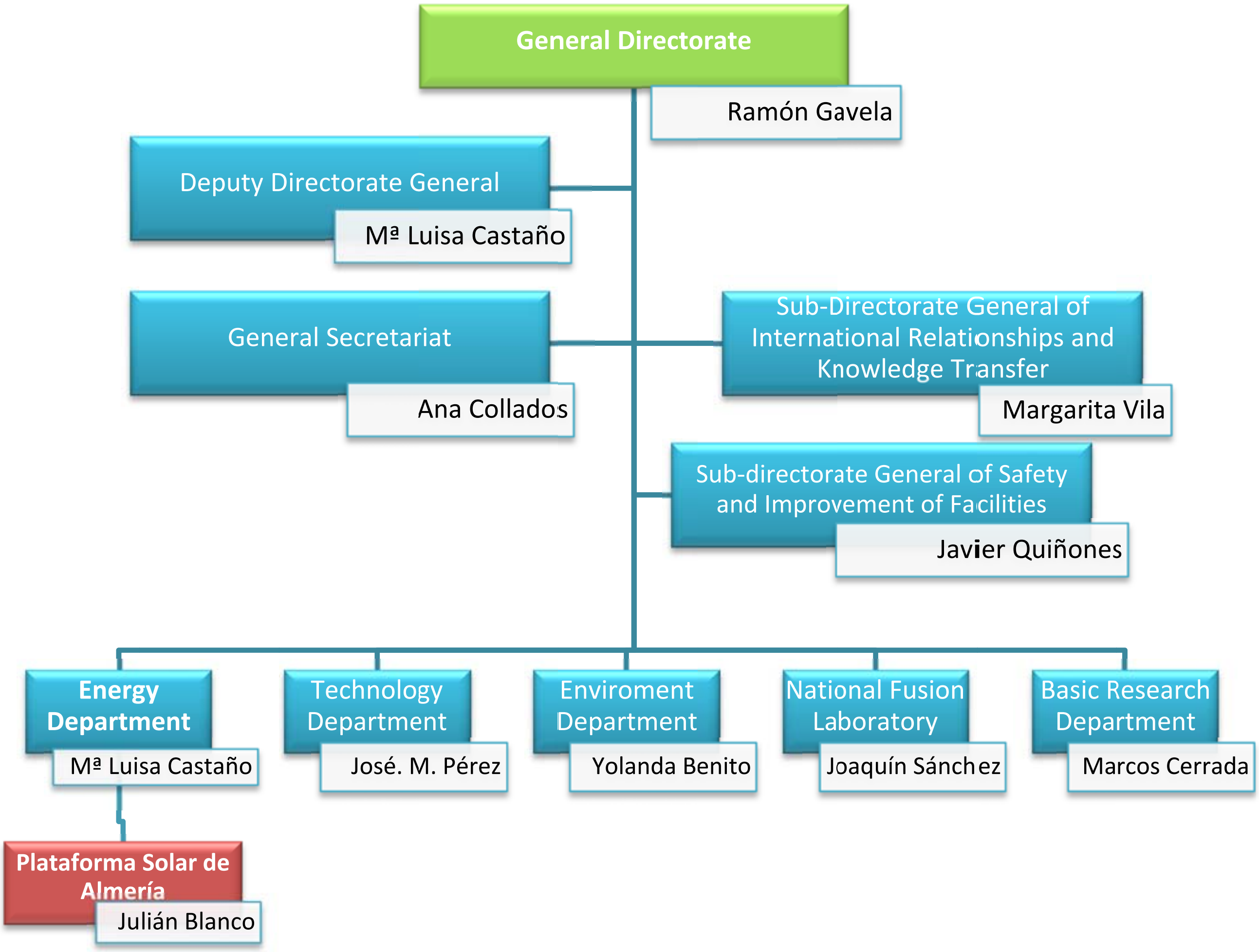

Figure 1. Integration of the PSA in the CIEMAT organization

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 technologies.
- Strengthen cost-reducing technological innovations contributing to increased market acceptance of solar thermal technologies.
- Promote North-South technological cooperation, especially in the Mediterranean Area.
- Assist industry in identifying solar thermal market opportunities.

Figure 2. Aerial view of the Plataforma Solar de Almería

Since 2017, research activity at the Plataforma Solar de Almería has been structured around four R&D Units:

- Solar Concentrating Systems. This unit develops and studies components for solar fields, complete systems and applications of concentrated solar thermal energy technologies, for electricity generation and industrial process heat.
- Solar Desalination. Its objective is to develop brackish water and seawater solar desalination.
- Solar Water Treatment. Exploring the chemical possibilities of solar energy, especially its potential for water detoxification and disinfection.
- Thermal Storage & Solar Fuels. The objective of this Unit is to provide solutions to concentrating solar thermal systems to become a dispatchable technology, by thermal storage systems and/or Hydrogen production by thermochemical processes.

Supporting the R&D Units mentioned above are the Direction and Technical Services Units. These units are largely self-sufficient in the execution of their budget, planning, scientific goals and technical resource management. Nevertheless, these 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. The Director's Office, on its part, must ensure that the supporting capacities, infrastructures and human resources are efficiently distributed. It is also the Director's Office that channels demands to the different support units located at the CIEMAT's main offices in Madrid.

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 134 persons that as of December 2017 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. Of the 126 people who work daily for the PSA, 70 are CIEMAT personnel, 13 of whom are located at the main offices in Madrid.

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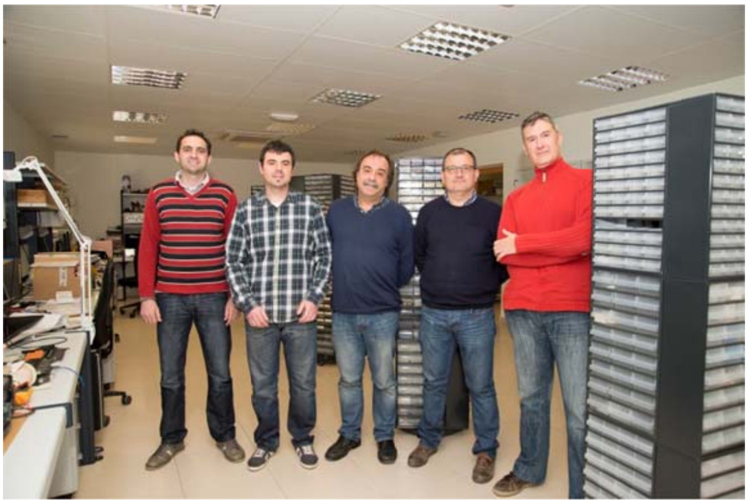
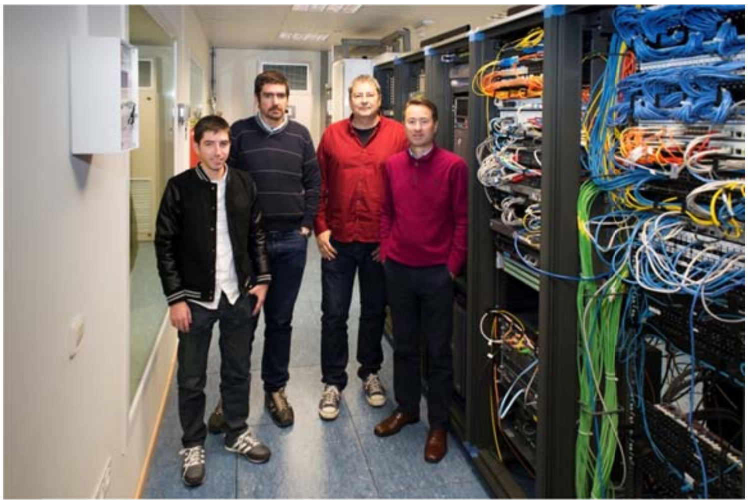




e)

f)

Figure 3. Management and technical services staff grouped in the PSA Management Unit. a) Direction Unit, b) Administration unit, c) Instrumentation unit, d) IT Services unit, e) Operation unit, f) Cleaning and maintenance unit, f) Infrastructure unit

In addition, the 10 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 are made up of a not less important group given the centre's characteristics. They are personnel who work for service contractors in operation, maintenance and cleaning in the different facilities. Of these 32 people, 15 of them 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.

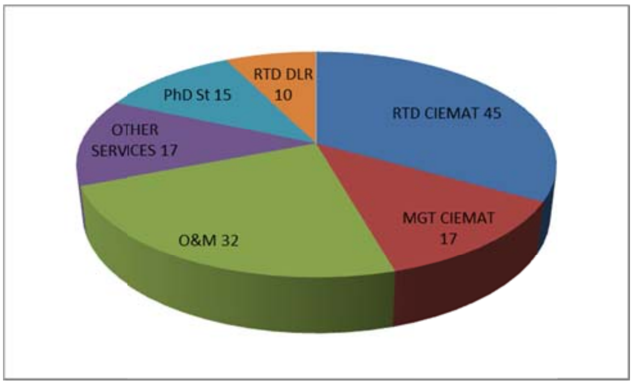


Figure 4. Distribution of permanent personnel at the PSA as of December 2017

The effort CIEMAT has made for 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 expense budget has an upward trend, in large part due to higher income, both from European Commission project funding, and from the National Plan for RD&I, although the most important factor was the increase in revenues from research contracted by business.

The PSA operating budget in 2017 totals 4.3M Euros (not including R&D personnel or new infrastructure).

2. FACILITIES AND INFRASTRUCTURE

2.1 EXPERIMENTAL INSTALLATIONS AND LABORATORIES EXISTING AT PSA FOR SOLAR THERMAL CONCENTRATING SYSTEMS

2.1.1 PSA EXPERIMENTAL FACILITIES FOR SOLAR THERMAL CONCENTRATING SYSTEMS

At present, the main test facilities available at the PSA related to solar thermal concentrating systems are:

- CESA-1 and SSPS-CRS central receiver systems, 6 and 2.5-MWth respectively.
- DISS 2.5-MWth test loop, an excellent experimental system for two-phase flow and direct steam generation for electricity production research with parabolic-trough collectors in different working conditions, up to 500ºC and 100bar.
- The FRESDEMO “linear Fresnel” technology loop.
- An Innovative-Fluids Test Loop, named IFL
- TCP-100 2.3-MWth parabolic-trough collector field with associated 115-m3 thermal oil storage system
- The Parabolic Trough Test Loop (PTTL) facility
- A parabolic-trough collector test facility with thermal oil (the so-called HTF Test loop) for qualification of components and complete collectors.
- 4-unit dish/Stirling facility, named DISTAL, and 2 EuroDish units.
- A group of 3 solar furnaces, two of them with horizontal axis (60 kWth and 40 kWth) and a third one with vertical axis (5 kWth).
- A test stand for evaluation and qualification of small parabolic trough collectors, named CAPSOL.
- A molten salt test loop for thermal energy systems, named MOSA

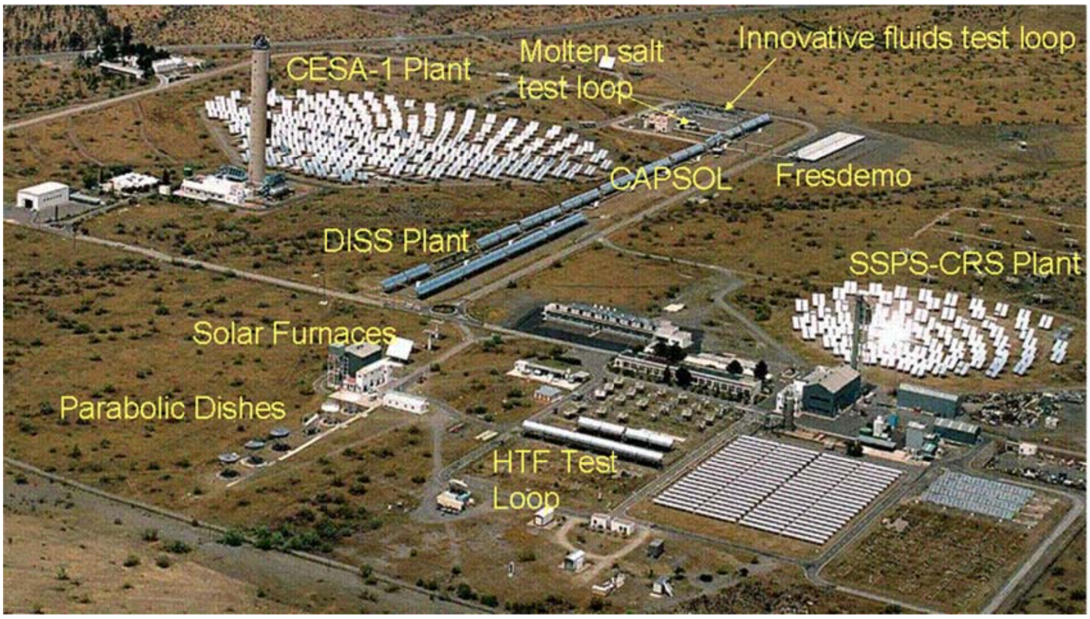


Figure 5. Location of the main PSA test facilities for solar thermal concentrating systems

These experimental installations and other with less importance are described in detail in next sections, grouped by the type of technology used (Central receiver systems, Line-focus collectors and Parabolic Dishes), having a special section for the Solar Furnaces for very high concentration and/or temperature tests.

2.1.1.1 *CENTRAL RECEIVER FACILITIES: CESA-1 AND CRS*

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 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.

Figure 6. The CESA-I facility seen from the North

Direct solar radiation is collected by the facility's 330 x 250-m south-facing field of 300 39.6-m2 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. In spite of 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.

To the north of the CESA-1 solar field 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 MWth at a typical design irradiance of 950 W/m2, achieving a peak flux of 3.3 MW/m2. 99% of the power is focused on a 4-m-diameter circle and 90% in a 2.8-m circle.

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 kWth capacity range.

The heliostat field is composed of 91 39.3 m2 first generation units manufactured by Martin-Marietta. A second field north of it has 20 52-m2 and 65-m2 second-generation heliostats manufactured by MBB and ASINEL.

Figure 7. Aerial view of the experimental SSPS-CRS facility.

The original SSPS-CRS heliostat field was improved several years ago with the conversion of all of 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. 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 actually 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/m2, total field capacity is 2.5 MWth and its peak flux is 2.5 MW/m2. 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.

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 (29dm3/s, 8bar), pure nitrogen supplied by two batteries of 23 standard-bottles (50dm3/225bar) each, steam generators with capacity of 20 and 60kg/h of steam, cooling water with a capacity of up to 700 kW, demineralized water (ASTM type 2) from a 8m3 buffer tank for use in steam generators or directly in the process, and the data network infrastructure consisting of Ethernet cable and optical fibre.


Figure 8. An autonomous heliostat in the CRS field.

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.

2.1.1.2 *LINEAR FOCUSING FACILITIES: HTF, DISS, INNOVATIVE-FLUIDS TEST LOOP, FRESDEMO, CAPSOL, KONTAS AND PROMETEO*

At present, PSA has several linear-focusing solar collector facilities for both parabolic-trough and Linear Fresnel collectors. Many of these experimental installations, such as the innovative-fluids test loop or the DISS plant, are the only one of their kind in the World, and place the PSA in a privileged worldwide position for research and development of new parabolic-trough collector applications. The main characteristics of these facilities are briefly explained below.

The HTF Test Loop

The HTF test loop was erected in 1997 and 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 several solar collectors of 75-m long connected in parallel (up to three collectors can be installed in parallel), being able to operate only one at a time. 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 5º. The thermal oil used in this facility (Syltherm 800®) has a maximum working temperature of 420°C and a freezing point of - 40ºC.

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 inertisation.
- 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 an European consortium with the financial aid of the European Commission was installed and evaluated under real working conditions at this facility in 1998 and it 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 study the optical and thermal performance of complete parabolic-trough collectors (optical efficiency, IAM coefficient, and global efficiency/heat losses) and receiver tubes.

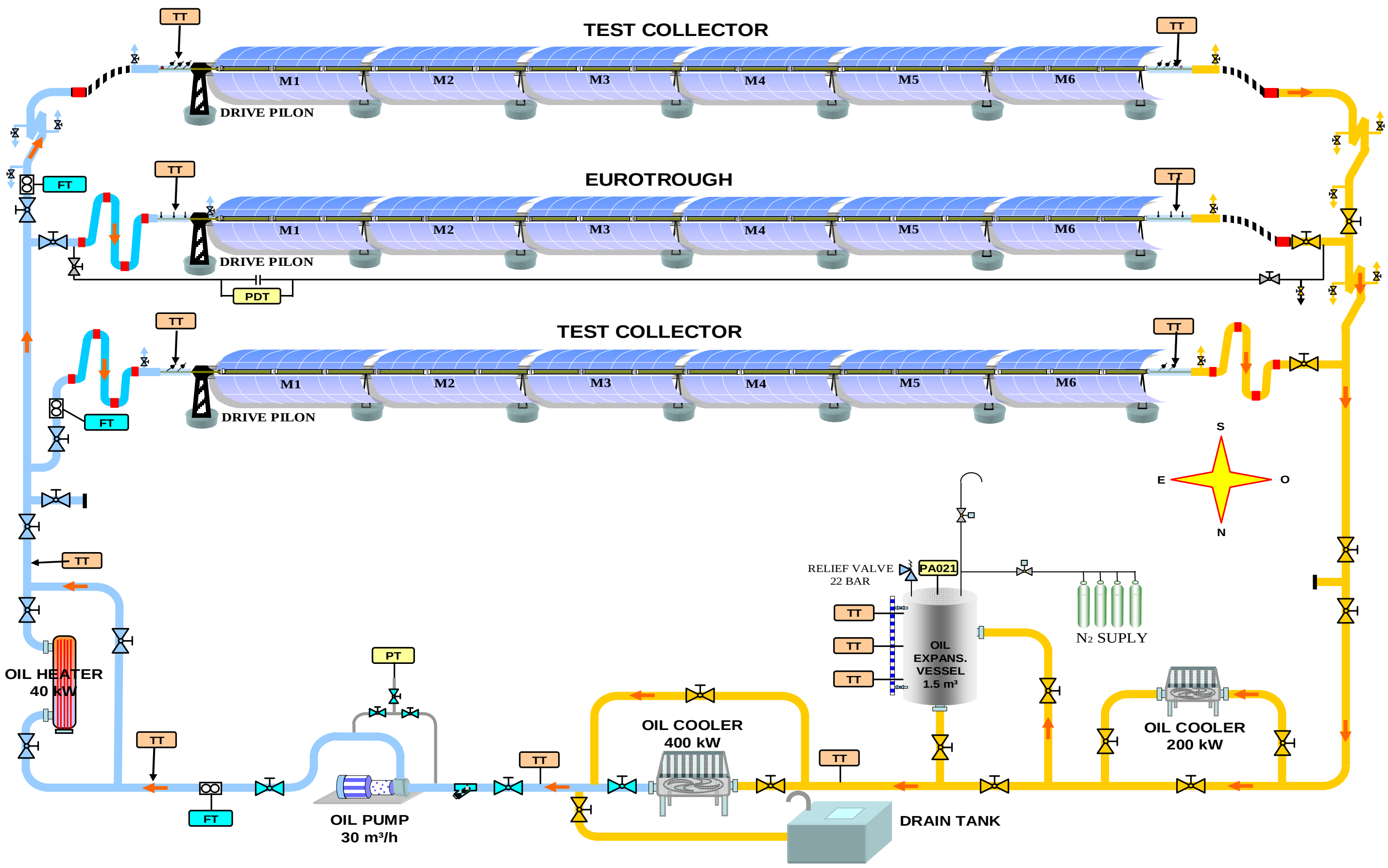


Figure 9. Diagram of the PSA "HTF test Loop".

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/400ºC) 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) consists of two subsystems, the solar field of parabolic-trough collectors and the balance of plant (BOP). In the solar field, feed water is preheated, evaporated and converted into superheated steam at a maximum pressure of 100 bar and maximum temperature of 400ºC as it circulates through the absorber tubes of a 700-m-long row of parabolic-trough collectors with a total solar collecting surface of 3.838 m2. 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).

In 2012, within the DUKE Project, three additional parabolic-trough collectors were installed in the solar field and all the absorber tubes were replaced by new ones, to increase up to 500°C the temperature of the superheated steam produced, enabling to generate direct steam at 100bar and 500°C.

Facility operation is highly flexible and can work from very low pressures 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 in 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.

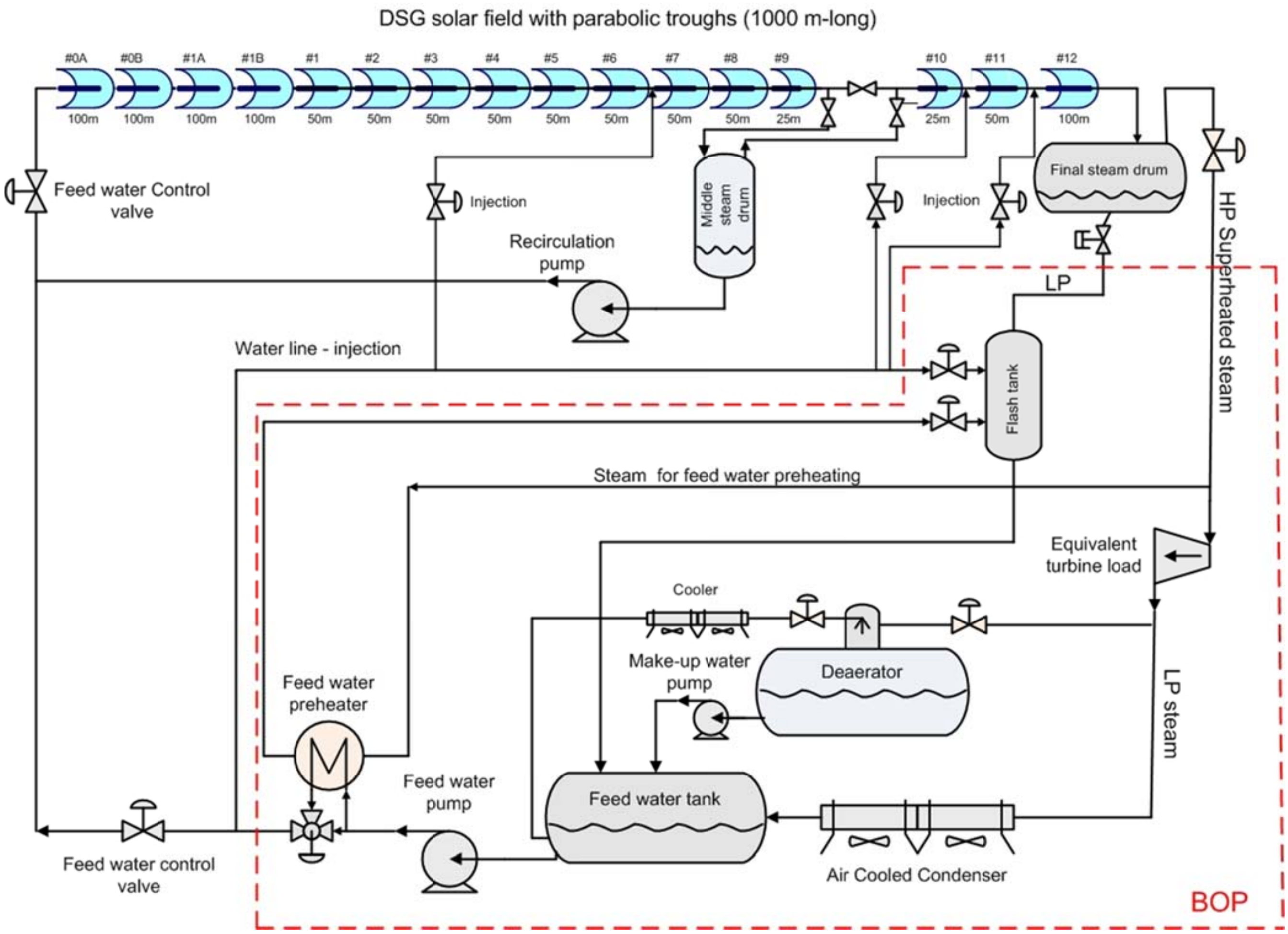


Figure 10. Simplified flow diagram of the PSA DISS loop

Amongst 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 flexholes, 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 this type of solar field.
- Thermo-hydraulic study of two-phase of water/steam in horizontal tubes with non-homogeneous heat flux.

Figure 11. View of the DISS plant solar field in operation

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 is located north of the DISS experimental plant control building, which houses the equipment necessary for its control and data acquisition.

Figure 12. View of the IFL experimental facility (with parabolic-troughs) using compressed gas as heat transfer fluid.

The IFL facility was originally designed to work at pressures and temperatures of up to 100 bar and 400ºC, and consists of the following components:

- Two East-West-oriented EUROtrough parabolic-trough collectors, each 50 m long with a 274.2-m2 collector surface. The collectors are connected in series.
- 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.
- A blower driven by a 15-kW motor which 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.

Since testing at 400ºC was successfully completed at the end of 2009, this facility was then upgraded to achieve temperatures of up to 515ºC and it was 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. This increase in test loop design conditions to 100 bar and 515ºC made the implementation of different improvements necessary (conventional absorber tubes in one of the two collectors were replaced with advanced high-temperature tubes, stainless steel pipes were installed for the high temperature zone and changes were made in the control system).

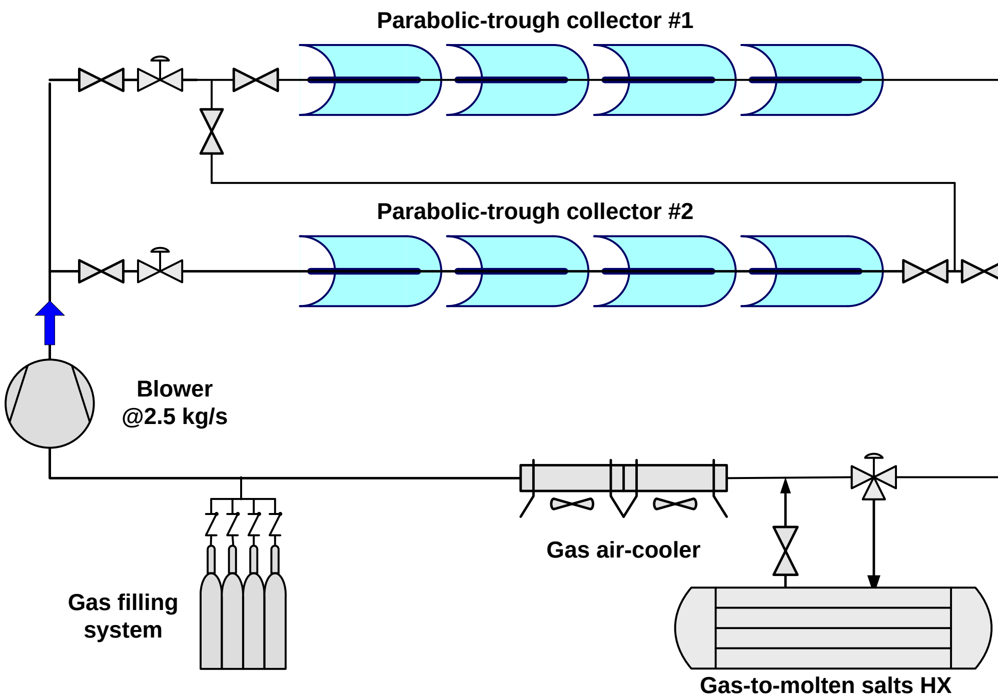


Figure 13. Simplified system diagram of the IFL experimental facility located at the PSA.

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 thermocline storage tank with 115 m3 of Santotherm-55 oil.

The TCP-100 solar field is composed of six parabolic trough collectors, model TER-MOPOWER, installed in three parallel loops, with two collectors in series within each loop. Each collector is composed of eight parabolic trough module 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 m2. The focal distance is 1.71 n, the geometrical intercept factor is ≥0.95, and the peak optical efficiency is 77.5%. The receiver tubes used in this solar field were delivered by Archimedes Solar Energy (Italy) and the working fluid is Syltherm-800.

The solar field is connected to a 10 m3 oil expansion tank for a maximum temperature of 400ºC. Thermal energy can be transferred from the solar field primary circuit to a thermocline oil storage tank with a total volume of 176 m3 and 115 m3 of Santotherm 55 oil with a maximum working temperature of 300°C.

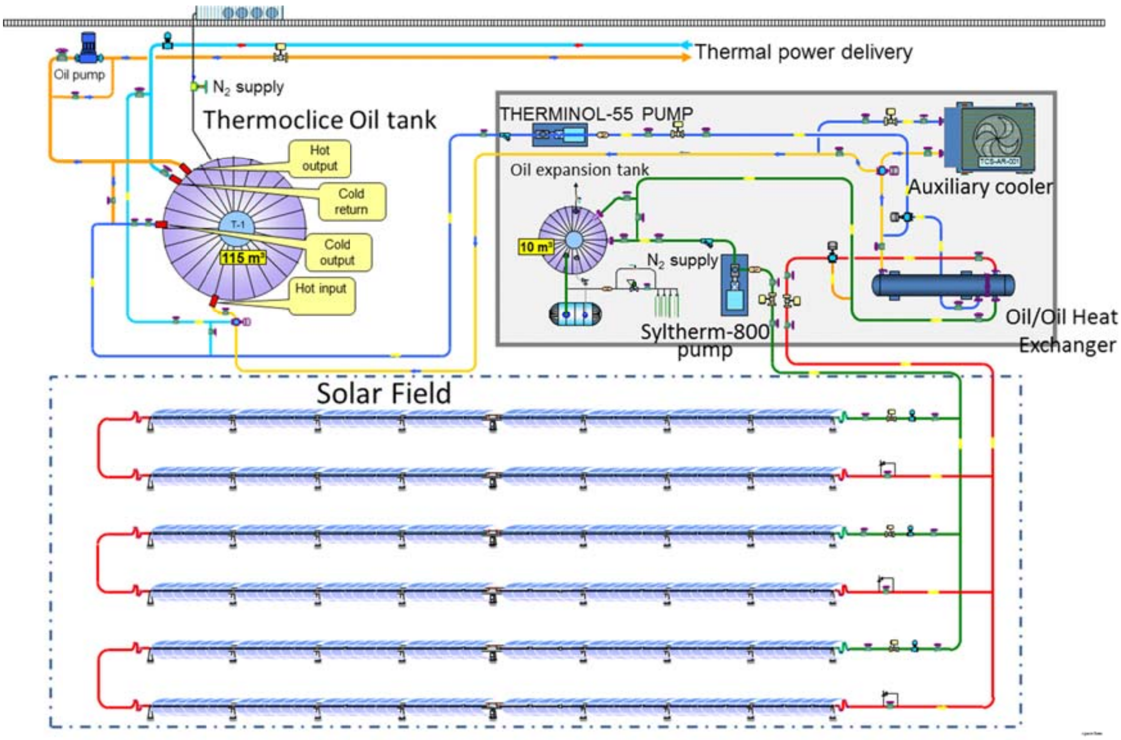


Figure 14. Diagram of the TCP-100 2.3-MWth parabolic-trough facility

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.

The Parabolic Trough Test Loop (PTTL) facility

This large test facility is implemented in a 420mx180m plot of the PSA and it is composed of two solar fields:

- the North field is designed to install with a 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.

Each field is provided with a complete oil circuit installed on a 30mx30m concrete platform between the two fields, and both circuits share: an oil expansion tank with a capacity of 30 m3, 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 m3/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 40ºC, oil piping connecting the circuit to the common elements (i.e., expansion tank and oil heater).

- South field: one oil pump (125 m3/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

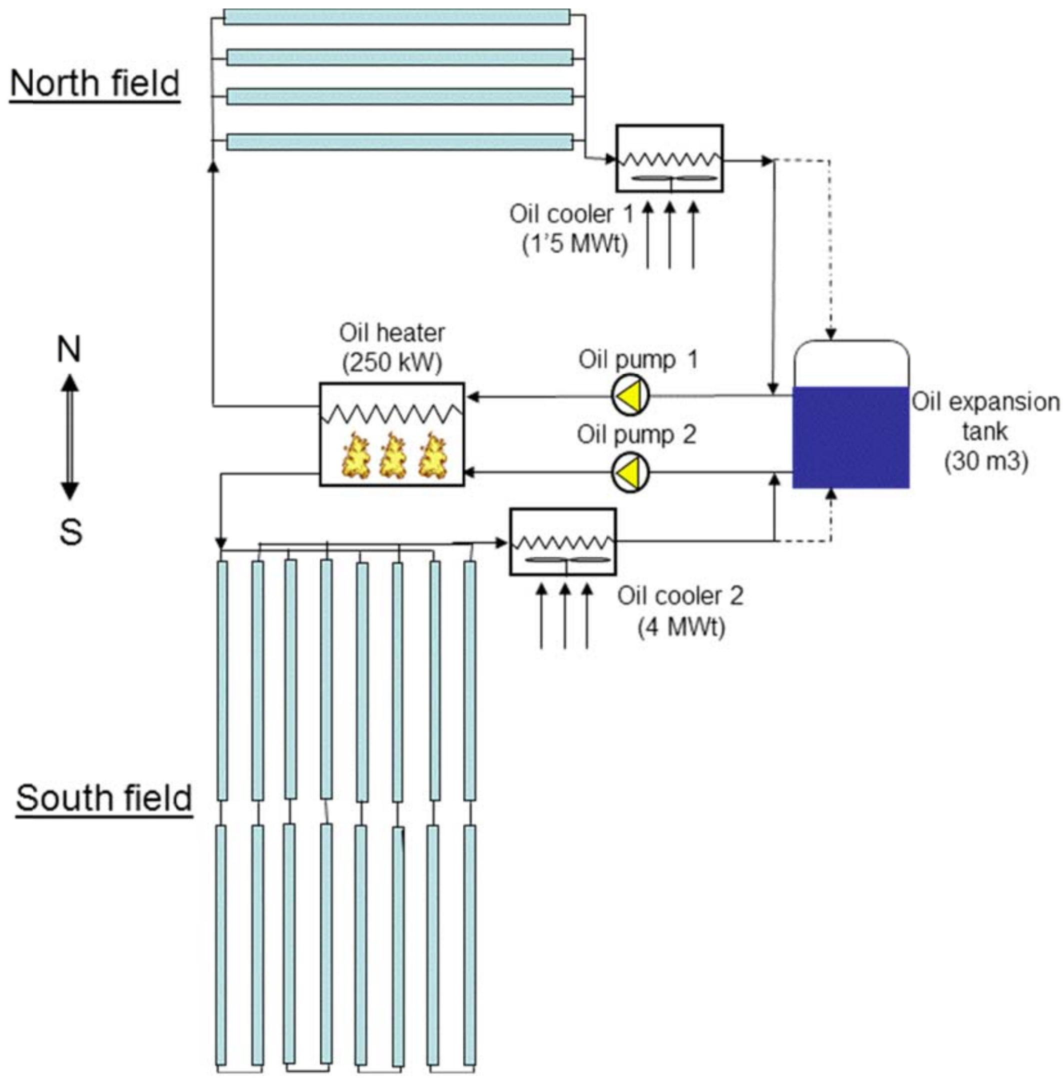


Figure 15. Simplified scheme of the PTTL facility

The FRESDEMO Loop

The FRESDEMO loop is a "Linear Fresnel concentrator" technology pilot demonstration plant. This 100m-long, 21-m-wide module has a primary mirror surface of 1433 m2, distributed among 1200 facets mounted in 25 parallel rows spanning the length of the loop. This collector loop is designed for DSG at a maximum pressure of 100 bar and maximum temperature of 450°C.

This pilot facility is presently connected to the piping system of the PSA DISS plant from where it is supplied with solar steam at different pressures and temperatures for testing in the three working modes: preheating, evaporation and superheating.

CAPSOL Facility

CAPSOL is a concentrating solar thermal energy test facility designed and built at the PSA for testing of small-sized, high-precision parabolic-trough solar collectors under real environmental conditions.

Figure 16. Photo of the linear Fresnel concentrator erected at the PSA.

The facility is designed to operate with pressurized water under a wide range of operating conditions: fluid temperatures from ambient to 230ºC, flow rates from 0.3 to 2.0 m3/h and pressures up to 25 bar. It also allows testing of different collector orientations and sizes (apertures up to 3 m). High-precision instrumentation has been installed for measuring all of the parameters required for adequate evaluation of parabolic-trough collectors. In particular, the facility has a mass flowmeter (Coriolis-type, with a ±0.1% measurement accuracy), a pyrheliometer (Eppley, with 8 µV/Wm-2 sensitivity) and two types of temperature sensors at the inlet and outlet of the solar field (4-wire PT-100 with an accuracy of ±0.3°C in a 100 to 200°C range). In addition to these instruments, the facility has sensors for measuring other parameters, such as fluid temperature at various points in the circuit, pressure, tank level, ambient temperature, wind speed and direction, etc.

This test facility makes it possible to find the efficiency parameters required for characterizing small parabolic-trough collectors: peak optical-geometric efficiency, incident angle modifier, overall efficiency and thermal losses when collectors are out of focus. The stationary state conditions needed for performing these tests are reached thanks to the inertia of the expansion tank and auxiliary heating and cooling systems. The data acquisition and control system facilitates monitoring and recording of the parameters measured as well as system operation from the control room.

Both complete small-sized parabolic-trough collectors and their components, such as absorber tubes, reflectors or tracking systems, can be tested in this facility. Furthermore, the facility also allows analysis of technical aspects of the collectors, such as materials durability, structural resistance, component assembly, etc. under real operating conditions.

Figure below shows a photo of the CAPSOL test facility with two prototypes of small-size parabolic-trough collectors installed.

Figure 17. CAPSOL solar thermal test facility for small-size parabolic-trough collectors.

KONTAS: Rotary test bench for parabolic trough collectors

A rotary test bench for parabolic trough collector components, KONTAS, was erected at Plataforma Solar de Almería 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 institutes.

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.

The 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 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 hot HTF collected on the way through the module and ensures a constant HTF temperature (±1K) 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 18. Side view of Kontas test bench and the heating cooling unit.

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

An experimental closed loop is installed at the North-East area of the Plataforma Solar de Almería. 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-PSA 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.

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 Syltherm 800® thermal oil as heat transfer fluid (HTF) 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 energy and ensures a constant HTF temperature (±1K) 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.

Figure 19. View of the PROMETEO test facility.

2.1.1.3 *PARABOLIC DISH SYSTEMS*

Accelerated ageing test bed and materials durability

This installation consists of 3 DISTAL-II type parabolic dish units, with 50 kW total thermal power and two-axis sun tracking system, In the 3 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: materials tests, air-cooled volumetric receivers tests (metal or ceramic), tests of small-size receivers prototypes with or without heat transfer fluid, etc.

The three parabolic dishes DISTAL-II (Figure 20) were erected at PSA in 1996 and 1997, using the stretched membrane technology. These parabolic dishes have a diameter slightly larger than the DISAL-1 above described (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 16,000 suns peak concentration at the focus). The tracking consists in a two-axis azimuth-elevation system.

Figure 20. View of a parabolic-dish DISTAL- II.

The test bed for durability and accelerated materials ageing is complemented with the Materials Laboratory existing at PSA, which is described in the laboratories section of this document (section 2.1.2.1), and with the durability and accelerated materials ageing laboratory existing at Madrid (section 2.1.2.6).

EURODISH

Under the Spanish-German EUROdish Project, two new dish/Stirling prototypes were designed and erected, 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 kWth maximum and a maximum concentration of 16.000 suns at the focus. The tracking system is azimuth-elevation.

Figure 21. Front and back views of the EURODISH

2.1.1.4 *THE SOLAR FURNACES AT PSA*

Solar furnaces can be defined as optical systems that concentrate solar radiation in a small area called focus where high temperatures and thermal fluxes can be reached. They can reach concentrations of over 10000 suns, the highest energy levels achievable in a solar concentrating system. Their main field of application are materials testing, either at room conditions, controlled atmosphere or vacuum, and solar chemistry experiments using chemical reactors associated with receivers.

A solar furnace essentially consists of a continuously solar-tracking, flat heliostat, a parabolic-dish concentrator, an attenuator or shutter and the test zone located in the concentrator focus.

The flat heliostat reflects the incoming solar beams on the parabolic-dish concentrator, which in turn reflects them on its focus (the test area). The amount of incident light is regulated by the attenuator located between the concentrator and the heliostat. Under the focus, a test table movable in three directions (East-West, North-South, up and down) places the test samples in the focus with great precision.

There are three solar furnaces fully operational at the PSA: Solar furnace SF60 which has been in operation from 1991, solar furnace SF5, in operation from 2012 and solar furnace SF40 which started operating in 2014.

SF-60 Solar Furnace

The SF60 consists basically in a 120 m2 flat heliostat that reflects the solar beam onto a 100 m2 parabolic concentrator which in turn concentrates the incoming rays on the focus of the parabola, where the tested specimens are placed. The incoming light is regulated by a louvered shutter placed between the heliostat and the concentrator. Finally a test table movable on three axis is used to place the specimens in the focus.

In this furnace, 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 only heliostat associated with the SF-60 consists of 120 flat facets, with 1 m2 reflecting surface each. These facets have been designed, manufactured, assembled and aligned by PSA technicians. Every facet is composed of a 1 m2 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. Figures 22 and 23 show the new heliostat and a detail of the back side of the facet respectively.

Figure 22. HT120 heliostat with new PSA facets.


Figure 23. Back side of facet.

The parabolic concentrator is the main feature of this solar furnace. It is made of spherically curved facets distributed along five radii with different curvatures depending on their distance from the focus. It concentrates the incident sunlight from the heliostat, multiplying the radiant energy in the focus.


Figure 24. HT120 heliostat in tracking.

The shutter (attenuator, see Figure4) consists of a set of horizontal louvers which turn on their axis to control the amount of sunlight incident on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter.

The test table is a mobile support for the test pieces or prototypes to be tested that is located under the focus of the concentrator. It moves on three axes (X, Y, Z) perpendicular to each other and positions the test sample with great precision in the focal area.

The combination of all of the components described lead to the flux density distribution in the focus which 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/m2 are: peak flux, 300 W/cm2, total power, 69 kW, and focal diameter, 26 cm.

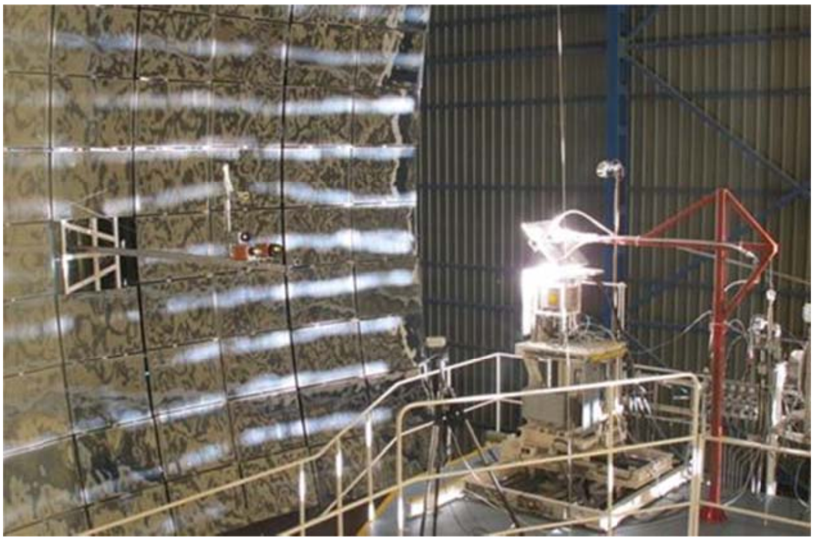


Figure 25. Interior view of the PSA SF-60 Solar Furnace in operation

SF-40 Solar Furnace

The new SF-40 furnace consists mainly of an 8.5-m-diameter parabolic-dish, with a focal distance of 4.5 m. The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive 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 basically consists of a 100 m2 reflecting surface flat heliostat, a 56.5 m2 projecting area parabolic concentrator, slats attenuator, 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 in focus is rotated 90º, 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, so that the specimens are not oxidized during tests.

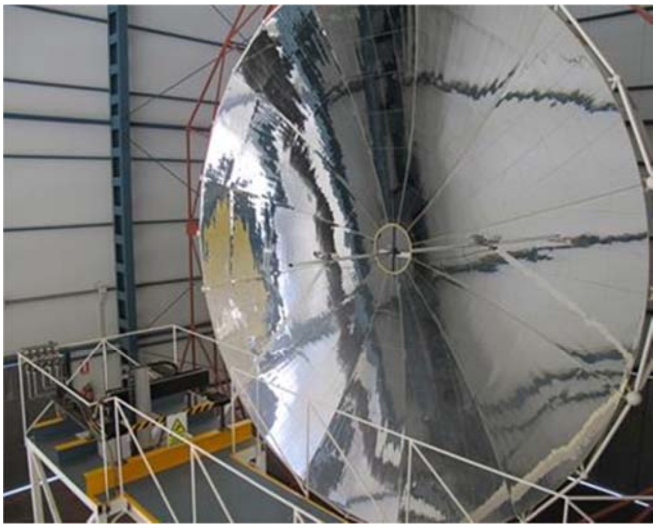


Figure 26. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

SF-5 Solar Furnace

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

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

It differs substantially from that 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 that in most existing solar furnaces, 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 a 8.7 m2 concentrator mirror, placed upside-down with the reflecting surface facing the floor, on a 18 m high metallic tower; in the centre of the base of the tower there is a 100 m2 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 louver attenuator is placed.

Figure 27. Concentrator of the SF-5 Furnace.

2.1.1.5 *THERMAL STORAGE FACILITIES*

MOSA: Molten Salt Test Loop for Thermal Energy Systems

Figure 28. Molten salt test loop.

This molten salt test loop is a replica of a thermal energy storage system with molten salts and a two-tank configuration. With 40t of molten salts plant, this facility consists basically in:

- Two tanks, one vertical, for hot molten salts, and another horizontal, for cold molten salts.
- A thermal oil loop that can be used for heating the salt up to 380oC and cooling it to 290oC.
- A CO2-molten salt heat exchanger for heating the salt up to 500oC with CO2 supplied by parabolic trough collectors.
- Two flanged sections, where different components for this type of loops (e.g. valves, flow meters, heat trace, pumps…) can be tested.

Being a set up which is a reduced scale of a commercial two-tank molten salt storage system, everything related to this type of systems can be tested in this facility.

For more information see: M. M. Rodríguez-García, and E. Zarza, “Design and Construction of an Experimental Molten Salt Test Loop”, Proceedings of the 17th International SolarPACES Conference, Granada, 2011.

Applications

- Checking of components (pumps, valves, flowmeters, etc.) for their use in a 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 heat exchangers for molten salt/gas.
- Characterization of thermocline tanks.

2.1.2 EXPERIMENTAL INSTALLATIONS FOR SOLAR DESALINATION UNIT

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 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 ºC with a maximum operating temperature of 70 ºC 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 (More details about the solar field are supplied within its specific subsection).

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 ºC, 56 mbar abs) produced 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 ºC, 10 bar abs), as well as operating the MED plant in the absence of solar radiation.

Figure 29. The PSA SOL-14 MED Plant (left), double-effect LiBr-H_2O absorption heat pump (upper right) and 606-m^2 flat plate solar collector field (bottom right)

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 behavior in the coupling with thermal desalination systems at 60-90 ºC 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 ºC 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 35º south orientation. Each row has its own filling/emptying system consisting in 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 ºC). The solar field has flow control valves that permit to have an equal distributed flow rate without further regulation. Also, 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 water tanks connected to each other for a total storage capacity of 40 m^3. This volume allows the sufficient operational autonomy for the fossil backup system to reach nominal operating conditions in the desalination plant.

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.

Figure 30. The 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II)

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 ºC and an auxiliary electrical power system that raises the temperature if required. The steam generators are able to 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 ºC (nominal flow rate of 119 kg/h, maximum flow rate of 360 kg/h) and at 0.16 bar/58 ºC (nominal flow rate of 195 kg/h, maximum flow rate of 360 kg/h). Both, the high and low-pressure steam can be used as motive and entrained vapor, respectively, in a train of four steam ejectors coupled to the PSA MED plant, simulating the behavior of a MED plant working with thermal vapor compression. 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.

Figure 31. View of the outside of the CSP+D test bed building with the air coolers (left) and partial view of the interior of the CSP+D test bench (right)

Facility for Polygeneration Applications

Polygeneration is an integral process with the purpose of producing two products from one or several 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 heating sanitary water (ACS).

The purpose of this facility is the preliminary study of the behavior 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 CSP+D requiring temperatures around 200 ºC. 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 ºC, and efficiency over 55% in the range of 120-220 ºC (for 1000 W/m^2 of direct normal irradiance).

The field is configured with 8 collectors placed in 4 parallel rows, with two collectors in series in 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 going to be used to generate steam for supplying the double-effect absorption heat pump coupled to the PSA MED plant.

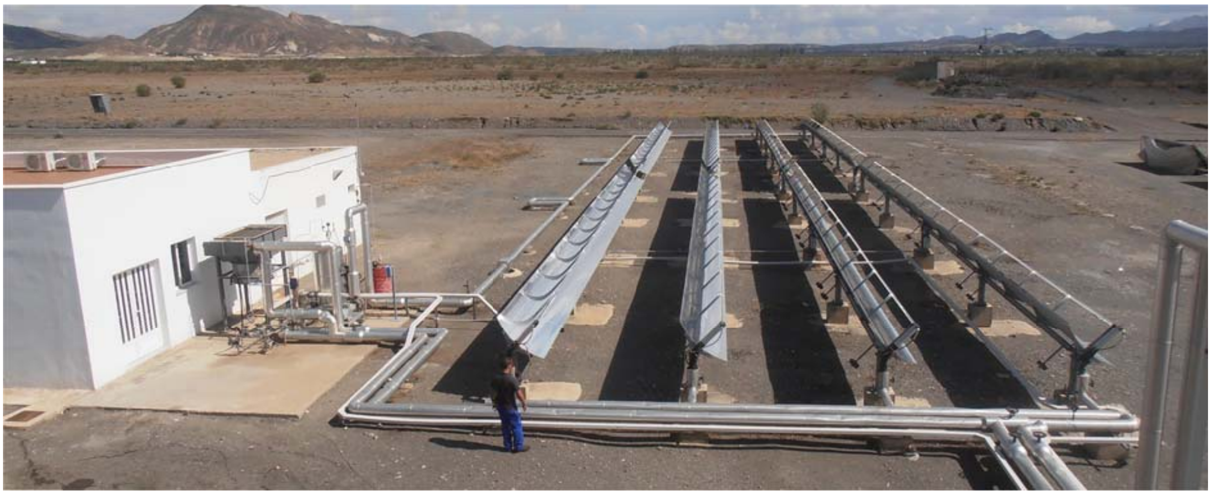


Figure 32. NEP PolyTrough 1200 solar field

Test-Bed for Solar Membrane Distillation Applications at Pilot-Scale

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, and 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 ºC.

Figure 33. Internal (left) and external (right) views of the Membrane Distillation experimental test bed within the PSA low-temperature solar thermal desalination facility.

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 open or closed loop. In the latter case, both the distillate and brine flows are collected and mixed together 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 all manufacturers. The list of MD modules that have been evaluated or are under evaluation is:

1. Plate and frame air-gap (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 membranes area 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).

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

The installation consists of a test-bed with a small plate and frame module that can be used for evaluating direct-contact, air-gap or permeate-gap membrane distillation. The module is made of polypropylene and designed so that the membrane can be replaced very easily. The module has 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. The effective membrane surface is 250 cm^2. 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 liters equipped with an electric heater (3 kW) controlled by a thermostat (90 ºC 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 ºC) controlled by temperature and water is circulated between a cold storage of 80 liters and the module. The circuit is heat insulated and fully monitored for temperature, flow rate and pressure sensors, connected to a SCADA system.

Figure 34. Bench-scale unit for testing membranes on isobaric MD

Bench-Scale Unit for Flat Sheet Membrane Distillation Testing

The facility is a high precision laboratory grade research equipment 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 cell size is sufficient for flow distribution and regime to be applicable to full scale MD technology.
2. Adjustable MD channel configuration to all channel variants (PGMD, AGMD, DCMD, VMD, VAGMD).
3. Temperature precision of 0.5 ºC.
4. Driving force temperature difference controllable.
5. Fully automated control system and large range of possible parameter settings by touch screen PLC.
6. Practical A4 format for membrane and condenser foil materials.

Figure 35. 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 in parallel. 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 have each a total effective membrane area of 100 cm^2, and hydraulic channels in zig-zag 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 36. Bench-scale unit for testing FO and PRO

Pilot Plant for Studying Combinations of Forward Osmosis and Reverse Osmosis

The plant has three different units that can be coupled in different ways between them: (i) a forward osmosis; (ii) reverse osmosis; (iii) microfiltration.

The forward osmosis (FO) unit uses a 4” spiral-wound Cellulose Triacetate (CTA) membrane with eleven membrane leaves of 1.5 m^2 surface each, supplied by HTI. The nominal flow rate is 3.6 m^3/h.

The reverse osmosis (RO) unit has 4 vessels that can be connected in series or in parallel, each of which hosting 4 membranes. The nominal flow rate is 3 m^3/h, and the pumping system is able to 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 a MF unit with 3 m^3/h nominal flow rate.

The installation is completely monitored with pressure sensors, conductivity and flow-meters, and 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.

Figure 37. Test bed for FO-RO combination research

2.2 LABORATORY OF SOLAR CONCENTRATING SYSTEM UNIT

The PSA Solar Concentrating Systems Unit has a large distributed laboratory covering several activity lines and provided with equipment located in Almería and Madrid. The activity lines included in this laboratory are the following:

- Durability and characterization of materials under concentrated solar radiation
- Development and testing of advanced optical coatings (i.e., selective and anti-reflective coatings)
- Solar reflectors durability analysis and optical characterization
- Receivers testing and characterization for concentrating solar thermal systems
- Solar hydrogen
- Radiometry
- Materials and components for molten salt circuits
- Material for Thermal Storage
- Geometrical characterization of solar concentrators

The equipment and capacities of this laboratory related to each of these activity lines are described in the next sections

2.2.1 DURABILITY AND CHARACTERIZATION OF MATERIALS UNDER CONCENTRATED SOLAR RADIATION

This activity line of the 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, fatigue and breakage of these materials at high temperatures under concentrated solar radiation.

The equipment associated to this activity is composed of devices located both indoor and outdoor. 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, every one of them dedicated to different kind of analyses:

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

The lab's equipment located in these rooms is listed below:

Metallography Room

- 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 75ºC 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 y 1.25 mm and 710, 630, 425, 315, 250, 160, 150, 90, 53 y 32 µm)
- Digital Camera with reproduction table

Figure 38. View of the Metallography Room in the Solar Furnaces building

Microscopy 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.
- 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 60Kg
- Balance: Mettler Toledo classic max 320g / min 10mg

(a)

(b)

Figure 39. View of a) the Microscopy Room, b) Thermogravimetric balance inside of its Room.

Thermogravimetry Room

- The thermogravimetric Balance SETSYS Evolution18 TGA, DTA, DSC (Temperature range ambient to 1750°C) 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 MicroGC simultaneously to the equipment. This thermogravimetic Balance has different possibilities of tests:

a) Tests under pure Hydrogen atmosphere up to 1750°C
b) Tests under pure Oxygen atmosphere
c) Tests under H_2O steam with other gases simultaneously.
d) Tests under corrosive atmosphere up to 1000°C

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

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;
- optical and electronic microscopes,

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 AMES and SCS units, and with the following specifications.

- Scanning electronic microscope (SEM) - Hitachi, model S-3400N II, high/low vacuum, secondary electron image, backscattered electron image, cooling stage and magnification 5x to 300.000x.
- Energy dispersive x-ray spectrometer (EDS) Quantax 400

Besides, the SEM room also has environmental secondary electron detector (ESED), a critical point dryer and sputterer.

The outdoor equipment is composed of several solar-dish concentrators located close to the PSA solar furnaces building. These solar dishes are used for thermal cycling under real solar conditions, with very high solar flux (up to 1200 kW/m^2) and high temperatures (from 200°C to 1200°C) and are equipped with different test benches for volumetric and tube configuration testing.

2.2.2 ADVANCED OPTICAL COATINGS

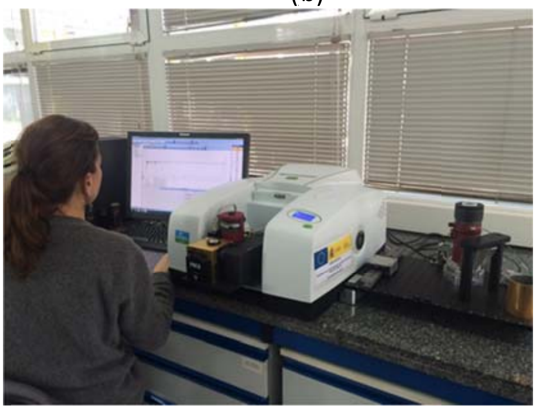
This laboratory line is devoted to the development and complete study of new selective coatings for absorbent materials used in solar concentrating systems at medium and high temperature (up to 600°C), as well as for anti-reflective treatments for glass covers used in some receiver designs, such as receiver 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 40a).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrated sphere manufactured by Pike (Figure 40b)
- *Portable Optosol absorber characterization equipment*: This equipment measures solar absorptance and thermal emittance of selective absorbers at 70°C, both on flat substrates and absorber tubes. The device for measuring absorptance has an integrating sphere with two detectors (Figure 40C). For measuring emissivity, it has a semi-cylindrical tunnel which emits infrared radiation at 70°C (Figure 40e).
- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (Figure 40d).
- BROOKFIELD LVDV-I+ Viscometer.
- KSV CAM200 goniometer for measuring contact angles (Figure 40f).
- 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 550ºC.

(a)

(b)



(c)

(d)

(e)

(f)

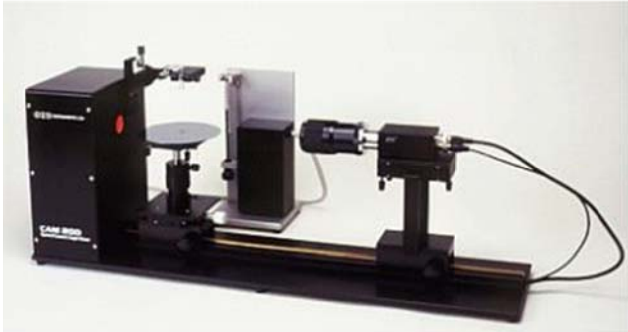


Figure 40. Advanced optical coatings laboratories equipment.

2.2.3 SOLAR REFLECTOR DURABILITY ANALYSIS AND OPTICAL CHARACTERIZATION

The PSA Solar Concentrating Systems Unit activity line on optical characterization and solar reflector durability analysis is the result of a joint collaborative initiative between CIEMAT and DLR called OPAC. It is provided with the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. These labs allow the characteristic optical parameters of solar reflectors and their possible deterioration to be determined. The optical analysis lab has the following equipment for the optical analysis of solar mirrors (see Fig. 4 left):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 660 nm at 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 460, 550, 650 and 720 nm and at different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- 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).
- Perkin Elmer Lambda 1050 spectrophotometer, with 150-mm integrating sphere and specular reflectance accessory with 0 to 68º incidence angles (URA).
- 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.
- Hitachi S3400 electronic scan microscope (SEM) with EDX analysis.
- 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 two solar reflector durability analysis labs are 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 Fig. 4 right). 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 simulation equipment is available for these accelerated ageing tests:

- ATLAS SC340MH weathering chamber for temperature (from -40 to+120ºC), humidity (from 10 to 90%), solar radiation (from 280 to 3000 nm) and rainfall of 340L.
- Vötsch VSC450 salt spray chamber with temperatures from 10 to 50ºC (450L).
- Erichsen 608/1000L salt spray chamber with temperatures from 10 to 50ºC.
- 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.
- KÖHLER HK300M acid rain chamber, 300 L and temperatures up to 70ºC and humidity up to 100%, to apply the Kesternich test.
- SC100 heatable 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 (335L, see Fig. 5).
- Ineltec CKEST 300 test chamber for humidity and condensation testing with temperatures up to 70ºC (300L).
- Memmert HCP108 weathering chamber to apply humidity (20-95 %) and temperature (20-90 °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 30ºm/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 analyze the possible detachment of the paint layers.
- Several devices for thermal cycles specially designed at the PSA.

Figure 41. OPAC solar reflector optical characterization lab (left) and durability analysis lab (right)

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 laboratories are 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.

Figure 42. Climate chamber with corrosive gases.

2.2.4 RECEIVERS TESTING AND CHARACTERIZATION FOR CONCENTRATING SOLAR THERMAL SYSTEMS

This activity line comprises both linear receivers and volumetric receivers. The equipment associated to linear receivers is located at PSA and main devices are a test bench called HEATREC (see figure 43, left) for measuring heat loss of single receiver tubes under indoor laboratory conditions and an outdoor test bench called RESOL (see figure 43, right) for measuring optical efficiency of single receiver tubes under natural solar radiation. Heat loss measurements can be done 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, 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 measures. The optical efficiency test is done by evaluating 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 a 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 lets 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.

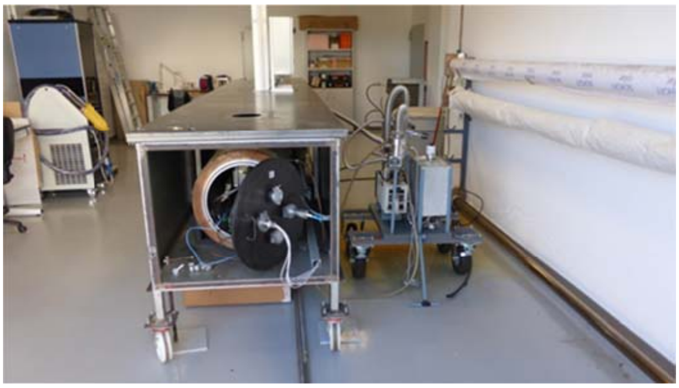


Figure 43. View of the HEATREC test chamber to measure heat losses in solar receiver tubes (left) and RESOL test bench to measure receiver's optical efficiency (right).

The lab equipment devoted to volumetric receivers is installed at CIEMAT-Moncloa (Madrid) site with the aim of studying in depth at lab scale the solar volumetric technology. Its main component is a test bench specially designed for the test of new volumetric absorbers and configurations and its ageing. This test bench has the flexibility to study:

- The pressure difference across the volumetric absorber for different fluid density and fluid velocity, for the determination of the main properties described by the Forchheimer extension to Darcy's law: the viscous permeability coefficient and, the inertial permeability coefficient. A differential pressure drop system is installed, with the previously described installation, for the properties determination
- 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.

The main equipment installed in this test bench (Figure 44) is:

- 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,
- Extraction system: with 1 k-type thermocouple, 1 PT100 sensor, an air mass flow-rate measurement, and an air blower.
- A 4-kW solar simulator, installed in CIEMAT-Moncloa made up of a Xenon lamp and a parabolic concentrator (Figure 45) that can reach fluxes of up to 1400 kW/m^2.

The lab-equipment described above to study volumetric receivers at atmospheric pressure is complemented by an indoor small facility to study thermal storage materials for high temperature using hot air as heat transfer fluid. This small facility is composed of a thermocline storage test bench (of about 0.1 m^3) as experimental loop for static (Figure 46) and dynamic (**¡Error! No se encuentra el origen de la referencia.**47) thermal characterization of porous beds.

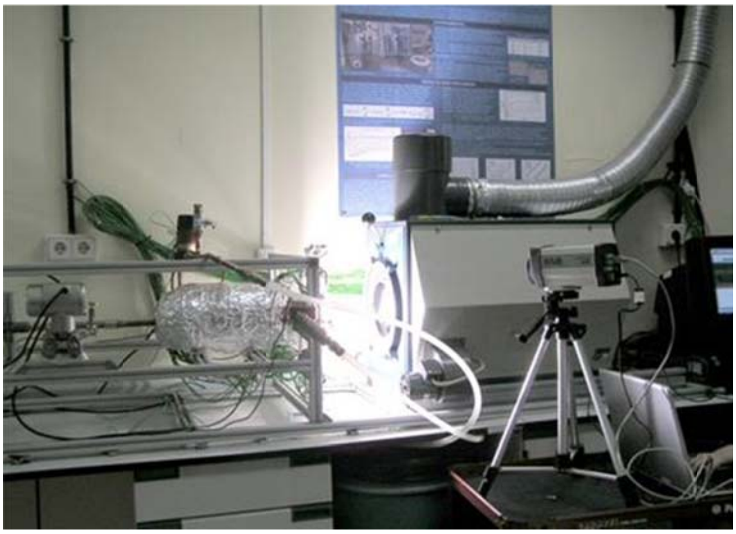


Figure 44. Test bench for volumetric receiver testing

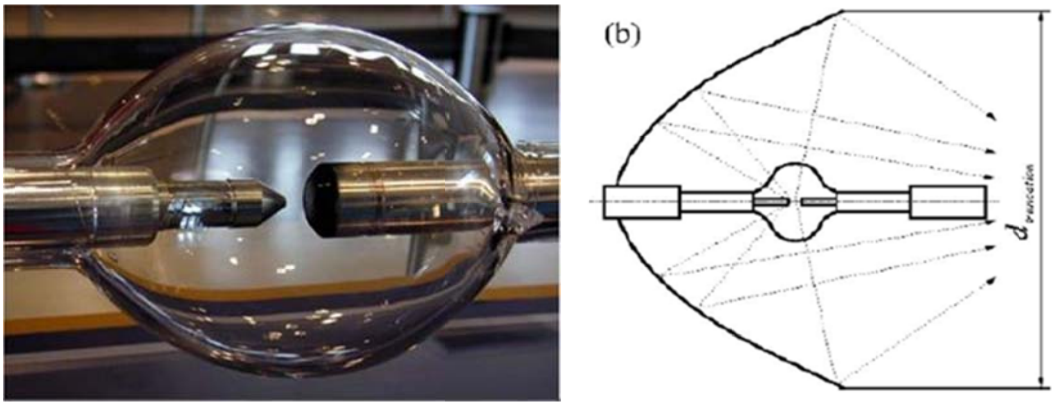


Figure 45. Xenon lamp used in the volumetric receiver test bench at CIEMAT (Madrid)

The system consists of six power heating resistors with a total power of 15000 watts electric energy. They heat the air up to a target temperature (maximum temperature limited by the resistor is 1000°C) by means of a temperature controller. An amount of 35 K-type thermocouples units of 400 mm long are used. The behaviour of the tank is measured at 7 levels with 5 measurement each level. The total power consumption is recorded, with a three-phase electrical measurement, to match the energy balances and the heat losses. Moreover, the external surface temperature mapping is registered by a thermograph camera, which offers a complete image of the external chassis of the tank.

The two possible configurations of this test bench are:

- Static configuration: In this configuration, the experimental loop allows the characterization of effective thermo-physical parameters of the bed; material thermal conductivity, thermal losses, stored energy, etc. for different filler materials,

Dynamic configuration: In this configuration, the experimental loop allows an agile characterization of the global storage at different working temperatures, filler materials, charges and discharges strategies, etc.

Figure 46. Front view of the lab-scale regenerative storage system in static arrangement.

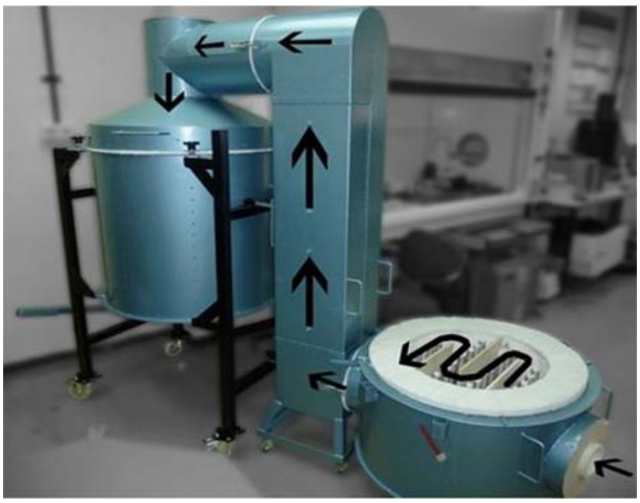


Figure 47. Front view of the lab-scale regenerative storage system in dynamic arrangement.

2.2.5 SOLAR HYDROGEN

Application of solar concentrating technologies to high-temperature processes is another field of enormous importance in PSA. The best known application so far is bulk electricity generation through thermodynamic cycles, but other applications have also been demonstrated, such as production of hydrogen and solar fuels.

Some high temperature endothermic reactions for converting solar energy into chemical fuels are been investigated by CIEMAT-PSA through a range of indirect water-splitting techniques, as well as hybrid systems involving solar-driven fossil fuels transformation to hydrogen.

Some specific activities are studied at the laboratory of the Solar Concentrating Unit to support at lab scale the PSA R+D activities related to solar hydrogen. These activities include the following topics: (1) Exploring new materials as candidates for thermochemical cycles and (2) Development of innovative solar reactors as fluidised bed reactors.

In the first category, some specific activities are foreseen, regarding:

-Materials characterization –Our research efforts are driven to search new materials, that improve kinetics and reduce working temperatures of current materials used in thermochemical cycles. These materials are synthesized in the laboratory (or commercial) and assayed for the thermochemical cycles under different reaction conditions.

Furthermore, in order to qualify these materials, it is of upmost importance to assess the damage induced by thermal shock on consecutive cycles. For this purpose, materials are subjected to cycling heating under well-controlled conditions. Several important physical–thermal, mechanical, and chemical properties of the relevant materials can be identified when assessing the influence of treatments onto a solid substrate

For material characterization, a versatile electric furnace loop is available at CIEMAT's Solar Hydrogen Laboratory in Moncloa (Madrid) shown in Figure 48.

Figure 48. Indoor Solar Simulation Loop for evaluation of materials for thermochemical cycles

The laboratory is equipped with the instrumentation necessary for evaluation of innovative processes for hydrogen production. Horizontal tubular furnace: high-temperature kiln with maximum operating temperature of 1600°C suitable for a variety of laboratory and pilot applications; coupled with a gas chromatograph (Varian CP4900) equipped with a molecular sieve column and a TCD detector, etc.

For special purposes, some other equipment's are available to complete the characterization of these materials: A Thermogravimetric Equipment STA 449 F1 for simultaneous TGA-DSC analysis. This equipment has two exchangeable furnaces: a SiC for high temperature reaction (1600°C) and water vapour kiln up to 1200°C. Finally, a temperature furnace perfectly suited for cycling candidates materials is available. This furnaces has special heating elements made of molybdenum disilicide providing temperatures of about 1650 ºC with a precise temperature control, also in the lower temperature range (Fig. 12).„

Figure 49. Thermogravimetry analyser and an a 1650 º C electric furnace

For outdoor tests a research bench has been designed and assembled outside the indoor facilities. This solar concentrating technology called "Double Reflection disc" has a fixed position of the focus allowing to test a fluidized bed.The optics consist of 864 mirrors (approx.15 x 12 cm) in nine concentric rings on a circular (Ø = 3.5 m) plane normal to the solar radiation. There are two sets of mirrors. The first set is fixed at a 45º angle from the optical axis with the reflected rays normal to it, and a second set of parabolic mirrors reflects these rays, concentrating them on the focus. Tests are performed at the focus of this small 200 W solar disc (Fig. 50) pursuing to advance in novel solar reactor concepts through the development of innovative solar reactors as fluidized bed reactors. Fluidized beds as chemical reactors present several advantages that include a high rate of heat and mass transfer, low pressure drops, and uniform temperature distribution.

The general goal for these tests is to improve the understanding of fluidized bed hydrodynamics by completing the following objectives: Determine the effects of bed height on the minimum fluidization velocity, compare the effects of material density on the minimum fluidization velocity.etc.

Figure 50. Outdoor Solar Double Reflection disc and a fluidised bed reactor on the focus

This facility is also applied to study novel thermochemical energy storage systems that employ fluidized beds of CaO/Ca(OH)2 for hydration/dehydration reactions. These systems have an important interest because of the inherent advantages of the low cost of the materials and their relatively high temperature operation windows (450 °C–550 °C). Some preliminary works have been conducted in this new pilot plant designed to test the concept under realistic reactor conditions.

This concept is being applied for some other chemical reactions by the construction, of a autonomous pilot plant called “Oresol” that can be operated in a solar furnace at PSA. The principal goal of this study is the development and testing of a solar powered fluidized bed reactor for the extraction of oxygen from lunar regolith. This is done by the reduction of one constituent of lunar soil, ilmenite (FeTiO3), with hydrogen, and the subsequent electrolysis of the obtained water (Fig. 51).

Figure 51. Testing of a ORESOL plant in a solar furnace to produce oxygen form regolite.

2.2.6 RADIOMETRY

The activity line devoted to Radiometry came up of the need to verify measurement 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. 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 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 and 1000ºC accurate to ±0.25% and with a resolution of 1ºC. 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 to 150ºC 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 52. View of the PSA Radiometry equipment.

Figure 53. IR sensor calibration using a black body.

2.2.7 MATERIALS AND COMPONENTS FOR MOLTEN SALT CIRCUITS

Molten salts are becoming not only a standard thermal storage medium, but also a working fluid for central receiver solar plants. However, there are still open questions regarding the durability of components and materials currently available at the market for molten salt circuits. Keeping this in mind, a specific activity line was implemented in the laboratory of Concentrating Solar System Unit for this purpose. The equipment associated to this activity is installed indoor at PSA and it is composed of two test benches, BES-I and BES-II (Figure 54) especially designed and manufactured for testing of valves, pressure transmitters and other molten salts components under real working conditions up to 600ºC and 40 bar. Components with a nominal diameter from 2” up to 6” can be evaluated in these test benches.

Figure 54. Test bench BES-I for evaluation of molten salt components.

2.2.8 MATERIALS FOR THERMAL STORAGE

The performance of phase change materials (PCM) for latent storage is usually evaluated with differential scanning calorimetry (DSC) or T-history techniques. Nevertheless it is important to check their behaviour under service conditions in order to assure their feasibility as storage media. For this purpose, the Concentrating System Unit has three set ups: HDR and AgH, where the PCM is tested in atmospheric air, and SUBMA (see Fig. 56), where the PCM is tested in inert atmospheres.

Figure 55. The HDR device

Figure 56. The SUBMA device

The main features of these devices are the following:

HDR:

- Small furnace under ambient air atmosphere
- Accurate control of heating/cooling rates
- Sample temperature monitoring
- Allows melting/freezing cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 2-5 g

SUBMA:

- Small closed device inside a furnace
- Allows tests under inert atmosphere (N2, Ar)
- Furnace temperature and gas flow control
- Sample temperature monitoring
- Allows melting/freezing cycles up to 500ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 30-40 g

AgH:

- Furnace under ambient air atmosphere
- Accurate control of heating and cooling
- Allows melting/freezing cycles up to 350ºC
- Subsequent cycles or cycles with stand-by periods
- Sample size: 10-20g

2.2.9 GEOMETRICAL CHARACTERIZATION OF SOLAR CONCENTRATORS

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 most of it incident on the receiver component (receiver tubes in parabolic-trough collectors, receivers in tower systems, parabolic dishes, Fresnel lenses, etc.). The laboratory of the Concentrating Solar Systems Unit 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
- Etc.

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 20mm f/2.8 USM and CANON EF 24mm f/2.8 USM lenses.
- Photomodeler Scanner 2012 photogrammetry software.

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

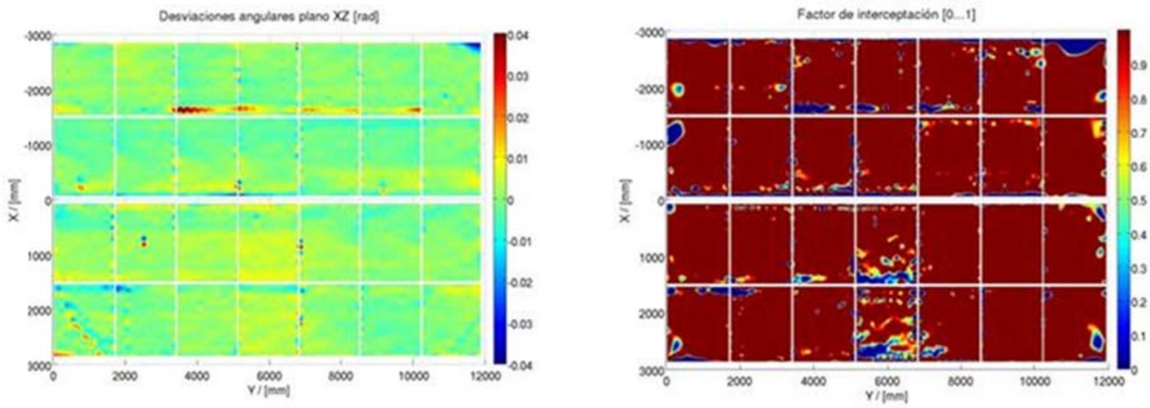


Figure 57. Angular deviations (left) and intercept factor (right) of a parabolic-trough collector module analysed by photogrammetry

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).

2.3 EXPERIMENTAL INSTALLATION FOR SOLAR DECONTAMINATION AND DISINFECTION OF WATER

The Research Unit of Solar Treatment of Water has different facilities and instrumentation related with the application of technologies for water purification (decontamination and disinfection). Since 2010, and as one of the activities co-funded by the Ministry of Science and Innovation under 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) and FEDER EC funding, the facilities were updated and new scientific instrumentation and facilities were acquired for Solar Treatment of Water activities (SolarNova Project).

2.3.1. SOLAR TREATMENT OF WATER UNIT FACILITIES

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

- Solar CPC (compound parabolic collector) pilot plants.
- Solar simulators
- Pilot plants for biological treatment.
- Ozonation pilot plant.
- Nanofiltration pilot plant.
- UVC-pilot plant.
- Test facility for photocatalytic production of hydrogen based on solar energy.
- Wet Air oxidation pilot plant.
- Experimental culture camera.

<u>Solar CPC pilot plants</u>

Since 1994 several CPC pilot plants have been installed at PSA facilities (Figure 58). 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 aluminum mirror with Compound Parabollic Collector (CPC) shape to optimize solar photons collection in the photo-reactor tube. The modules are place on a platform titled at 37º from the horizontal to maximize the global solar collection of photons through the year. In addition, the pilot plants may be 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.

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

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 (20-55ºC), 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 (20-55ºC), 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 module 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

a) 

b) 

Figure 58. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II.

As mentioned in table 1, CADOX photoreactor was hooked up to a 50L-ozonation system with an ozone production of up to 15 g O_3/h. It is completely monitored (pH, T, ORP, O_2, flow rate, H_2O_2, O_3) and controlled (pH, T, flow rate) by computer. 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 before treatment, 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 2m^2 CPC collector with 10 borosilicate glass tubes (50 mm diameter), illuminated volume of 25 L and a total volume of 40 L (Fig. 59) is connected to four electrocells for experimental research on electro-photo-Fenton processes for decontamination and disinfection of water.

Figure 59. Electro-Fenton pilot plant coupled with a 2 m^2 CPC (ELECTROX).

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 (Fig. 60). 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 photoreactors. The last presents 1.98 m^2 of irradiated surface with a recommended operating volume of 53 L. The whole pilot plant is equipped and automatically controlled by a UVA solar sensor. In addition, the pilot plant is equipped with a solar water heating panel which permits to increase the temperature of water prior to discharge it in the photoreactors.

Figure 60. 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 simulator 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) (Fig. 61).

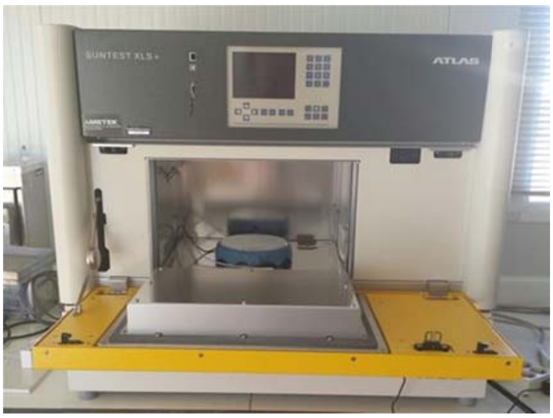


Figure 61. Solar simulator SUNTEST XLS+.

Ozonation pilot plant

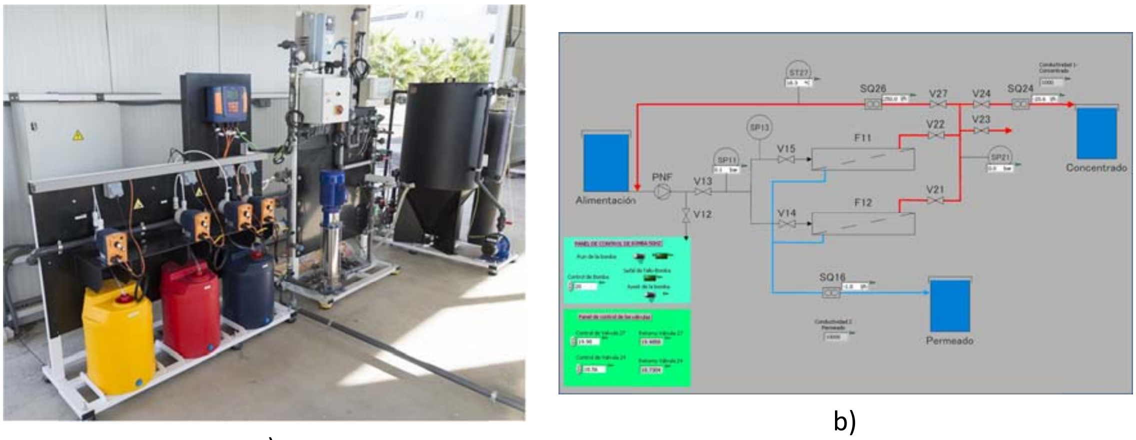
The ozonation system has a contact column reactor with total volume of 20L (minimum operation volume of 8L), reagents dosing system and pH automatic control. The pilot plant is equipped with pH and redox sensors, inserted in the recirculation line. In 2016, new instrumentation has been added to the ozonation pilot plant: (i) equipment for humidity elimination in the ozone gas outlet (Fig. 62.a); (ii) Thermo-catalytic ozone destructor (Fig. 62.b); (iii) dissolved ozone sensor (Fig. 62.c). This ozonation system works in batch mode allowing its combination with other technologies such as CPC photoreactors and the UV pilot plant.

a) **b)** **c)**

Figure 62. a) Equipment for humidity elimination in ozone gas outlet; b) Thermo-catalytic ozone destructor; (c) Dissolved ozone sensor.

Nanofiltration pilot plant

The nanofiltration (NF) system has two working modes, in series and in parallel. The basic system consisted of two FILMTEC NF90-2540 membranes, connected in parallel, with a total surface area of 5.2 m^2. These polyamide thin-film composite membranes work at a maximum temperature of 45ºC, a maximum pressure of 41 bar and a maximum flow rate of 1.4 $m^3 h^{-1}$, whereas operation pH range is 2-11. A third membrane was installed later and so the filtration total surface area was increased to 7.8 m^2. 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 (Fig. 63.a). In 2016 the nanofiltration system has been automatized by including electro-valves and automatic acquisition of the signals from the different instruments (flow, pressure, temperature, etc.) with the final aim of controlling by a computer (software Labview was employed, Fig. 63.b) the generation of permeate and concentrate flow rates.



a)

b)

Figure 63. a) Nanofiltration pilot plant photo; b) New lavbiew interface for control and automatic operation of the pilot plant.

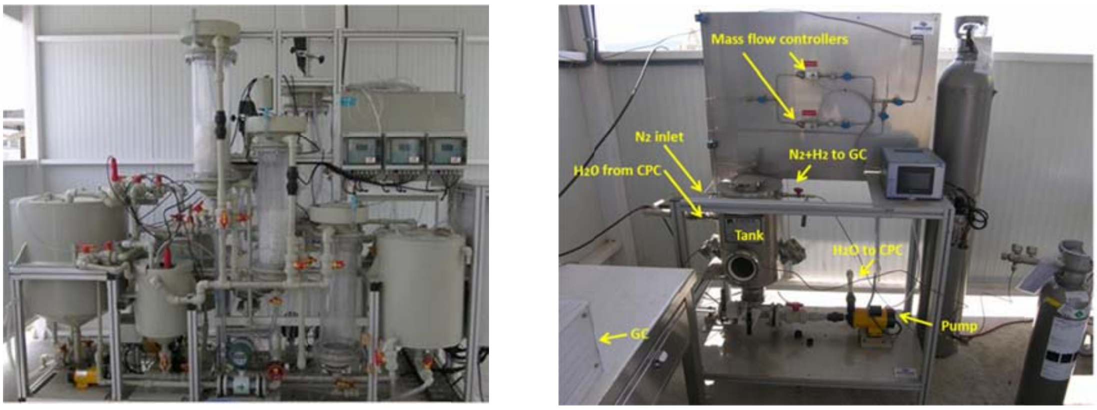
UVC-H_2O_2 pilot plant

Ultraviolet (UV) pilot plant was designed to treat and disinfect water for purposes and research and comparison with the solar technologies. This plant consists of three UV-C lamps (max. flow rate 25 m^3h^{-1}, 254 nm peak wavelength, 400 Jm^{-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 of this plant is 200-250 L, with illuminated volume of 5.5 L per lamp module. 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 (Fig. 64)

Figure 64. UVC pilot plant installed at PSA facilities.

Biological pilot plant

A biological pilot plant with a double depuration system (Fig. 65(a)) has an Immobilized Biomass Reactor (IBR) system with a total volume of 60-L: three IBRs of 20-L each one; and a Sequencing Batch Reactor (SBR) system: two SBRs 20-L each one. These modules use the same reception tank (200L) as well as the pH and oxygen dissolved 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 done by means of programmable relays and the main parameters are monitored by a SCADA system



a) **b)**

Figure 65. a) Biological pilot plant installed at PSA facilities. b) Solar pilot plant for photocatalytic generation of hydrogen

Photocatalytic generation of hydrogen pilot plant

This plant is connected to a CPC photo-reactor for the simultaneous removal of organic contaminants contained in aqueous solutions and hydrogen generation. The pilot plant consists on a stainless steel tank with a total volume of 22 L, 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 filling step. The CPC photo-reactor coupled with this system was described above in table 1 (Fig. 65 b).

Wet Air Oxidation pilot plant

A pilot plant designed and installed in 2016 as a harsh pre-treatment to reduce the complexity of industrial effluents and reaction time of a subsequent solar AOP. 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 1000 mL, 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 mixture.

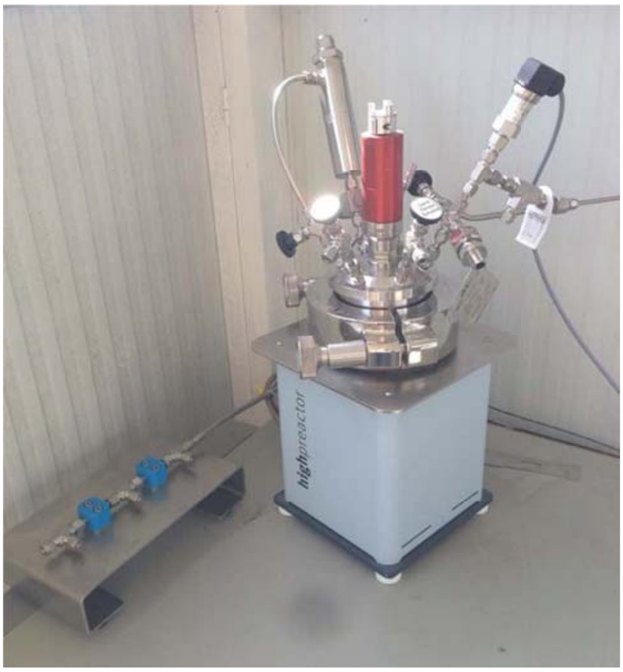


Figure 66. Wet Air Oxidation Pilot plant.

Solar UVA monitoring equipment

UV and global solar radiation data monitoring and storage system is composed by different pyranometers (Fig. 67), including global solar radiation in the range of 310 – 2800 nm (Kipp and Zonen CMP-6 with sensitivity 5 – 20 V W^{-1} m^{-2}, max. value: 2000 W m^{-2}), and the global UVA radiation in the range 300 – 400 nm (Kipp and Zonen CUV-5 with sensitivity 1 mV W^{-1} m^{-2}, max. value: 100 W 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.

Figure 67. CUV-5 radiometer (left). View of all solar UV radiometers (inclined and horizontal setup) used in the Solar Water Treatment Unit (right).

Cultivation chamber

The culture crop chamber of 30 m^2 is used for treated wastewater re-use experience since 2014 (Fig. 68). This controlled chamber is made of polycarbonate of 10 mm 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 4 individual areas of 3x2.5 m^2. 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. The measured of sensors (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 using the Ambitrol® software which permits to keep a comfortable temperature for crops approximately to 25ºC during the different seasons.

Figure 68. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities.

2.3.2 PSA WATER TECHNOLOGIES LABORATORY

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: two rooms for chemicals and other consumables storage. It is a 30-m^2 storeroom. It is organized on numbered and labeled 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 analyze the data from the experiments carried out at the PSA. In addition, 4 technical rooms are also part of the laboratory and are listed and described below:

- General lab
- Chromatography lab
- Microbiology lab
- Microscopy lab

General lab

The main laboratory is 94 m^2 (Fig. 69). It is equipped with four large work benches, two gas extraction hoods, a heater, a kiln, ultrasonic bath, three centrifuges, two UV/visible spectrometers, a vacuum distillation system, ultrapure water system, pH gauge and conductivity-meter, and precision-scale table. 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 *Vibrio fischeri* and activated sludge respirometry toxicity measurement devices, biodegradability measurement by two respirometers for suspended activated sludge and for immobilized activated sludge, and equipment for the analysis of BOD and COD. Jar-Test system for the optimization of separation of solids for water treatment.

Figure 69. General view of the new PSA Water Technologies Lab

Chromatography lab

This lab (Fig. 70(a)) is equipped with three high performance liquid chromatographs with diode array detector (HPLC-DAD and two UPLC-DAD) with quaternary pump and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which permits working with low concentration of pollutants and two ion chromatographs (Fig. 70(b): 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) analyzers by catalytic combustion at 670º C and total nitrogen (TN) analyzer with autosampler are also included. 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 analyze multiple samples from multiple experiments and identified possible chemical and biological markers (Fig. 70(c)).

a) 

b) 

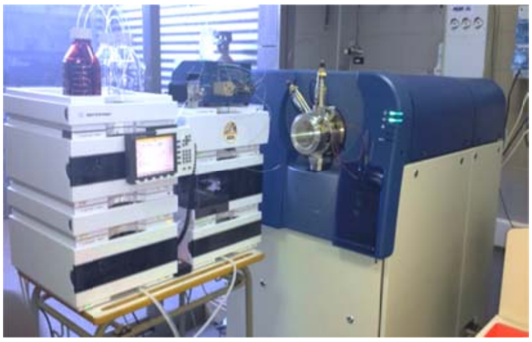
c)  d) 

Figure 70. a) General view of the chromatography lab at PSA facilities. b) Metrohm Ion chromatograph System. C) Agilent Ultra-fast UPLC-DAD analyzer. c) SCIEX TripleTOF 5600+ equipment

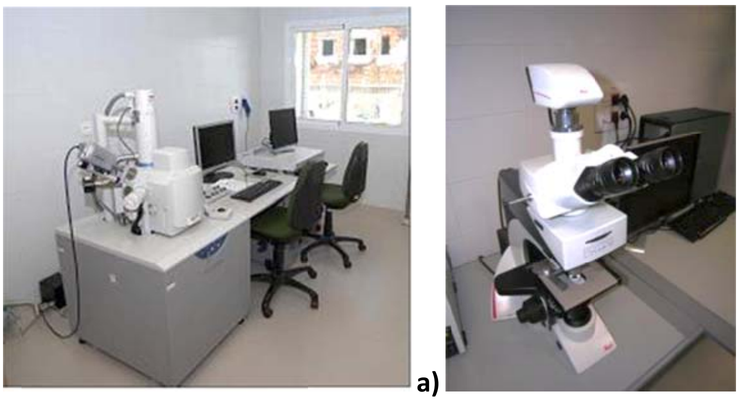
<u>Microbiology lab</u>

A 47-m^2 microbiology laboratory with biosafety level 2 (Fig. 71) is equipped with four microbiological laminar flow (class-II) cabinets, two autoclaves, three incubators, a fluorescence and phase contrast combination optical microscope with digital camera attachment. Besides, automatic grow media preparer and plaque filler and a filtration ramp with three positions are available. 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 is a reproducible way without any risk of cross contamination between samples.

Figure 71. General view of the microbiology lab at PSA facilities.

Microscopy lab

The microscopy lab is 11 m^2 room (Fig. 72(a)). A Scanning Electron Microscope (SEM) is located in this room. For the preparation of microbiological samples and catalysts to be analyzed in the SEM, the system is completed 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) FISH microscope (Leyca) with fluorescence module to develop the FISH (Fluorescent in situ hybridation) technique for visualization of DNA hibrydation with specific probes in live cells used for monitoring of key microorganisms within a heterogeneous population (Fig. 72(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 72. a) SEM (Scanning Electron Microscope). b) Optical microscope for FISH technique

2.4 EXPERIMENTAL INSTALLATIONS FOR THE ENERGY EFFICIENCY IN BUILDINGS R&D AT PSA

The Building Component Energy Test Laboratory (LECE), one of the facilities at the "Plataforma Solar de Almería" (PSA), is part of 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: 1.- Energy Analysis in Urban Environments, and 2.- 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.

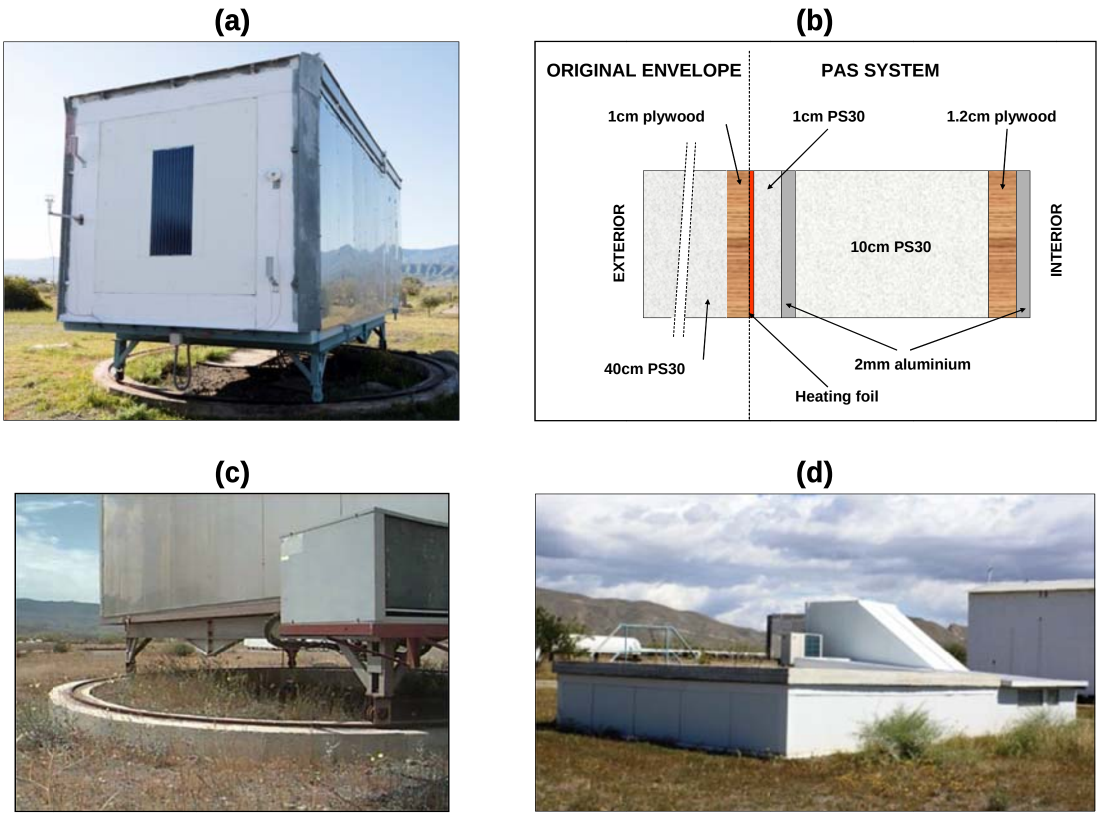


Figure 73. (a) CIEMAT's PASLINK test cell carrying out a thermal test of a PV module, (b) Schematic drawing of the PAS system, (c) Detail of the rotating device, (d) Exterior of the CETeB Test cell

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 in the test room consists of an aluminium sheet which makes it uniform 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 allowing 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.
5) Monozone building: This is a small 31.83 m^2 by 3.65 m high simple monozone 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.

(a) **(b)** **(c)**

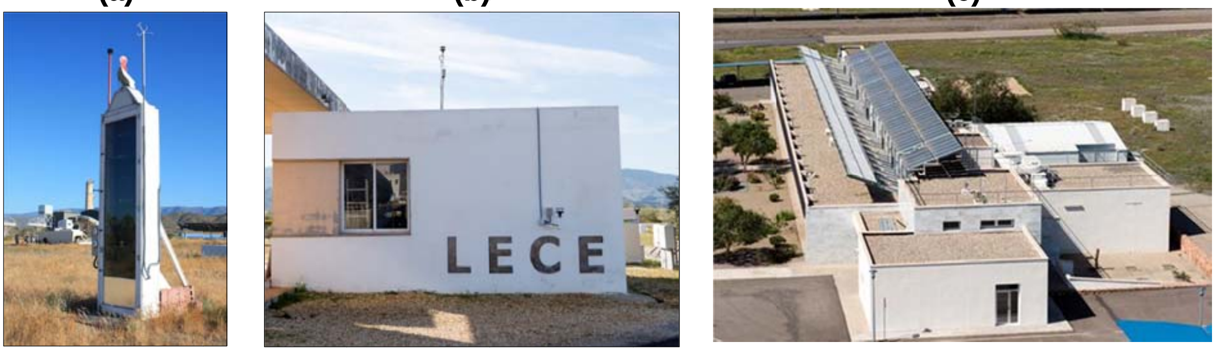


Figure 74. (a) Solar Chimney, (b) Reference monozone building, (c) ARFRISOL Building Prototype in use

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 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 1000 m^2 built area. One of them is also 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, conventional auxiliary systems to supply the very low demand that cannot be supplied with solar energy, using renewable energy resources, such as biomass insofar as possible.

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

3. SOLAR CONCENTRATING SYSTEM UNITS

3.1 INTRODUCTION

Activities performed by the Solar Concentrating Systems Unit (USCS) are aimed at promoting and developing concentrating solar thermal (CST) systems, both for power generation and for industrial processes requiring solar concentration, whether for medium/high temperatures or high photon fluxes. This PSA Unit is composed of four R&D Groups:

- Medium Concentration Group,
- High Concentration Group,
- Solar Fuels / Solarization of Industrial Processes Group, and
- Thermal Storage Group

We have been working in many projects in 2017: STAGE-STE, SFERA-II, CAPTURE, DETECSOL, ALCCONES, NEXTOWER, PRESOL, SITEF, SIMON, REELCOOP, DNICast, WASCOP, RAISELIFE, REPASCE and HYDROSOL-4. These R+D activities devoted to national and international R+D projects have been complemented with services rendered to clients requesting our technical&scientific support, for characterization of mainly new components. If the size of the staff of this PSA Unit (32 people) and the number of projects mentioned above are considered, it becomes evident the significant work load met in 2017.

A great effort has been devoted also to dissemination activities, and we have thus participated in many national and international conferences, workshops, seminars and Master courses to explain the benefits and applications of concentrating solar thermal systems. The effort devoted to standardization activities in former years has also continued in 2017 within the framework of the committees AEN/CTN206 and IEC/TC117.

Despite the rigid and very often senseless administrative rules imposed by the Spanish Administration to PSA since 2016, the USCS Unit has been at the forefront of the R+D sector devoted to CST technologies also in 2017. However, the continuous obstacles raised by these administrative rules and their incompatibility with the type of R+D activity that the USCS Unit must perform, led to a deep re-organization of this PSA Unit at the end of 2017. The new organization will be officially implemented in 2018.

Activities and results achieved in 2017 by the four R&D Groups of the PSA USCS Unit are summarized in the sections below.

3.2 PROJECTS

ESTCI. Concentrating Solar Thermal Energy for Iberoamerica

Participants: CIEMAT (Spain), CENIDET (Mexico), DICTUC (Chile), EPM (Colombia), Grupo Ibereólica (Spain), PUCC (Chile), SOLINOVA (Brazil), UAEMex (Mexico), UFPE (brazil), UNAM (Mexico), UNINORTE (Colombia), UNLP (Argentina)

Contact: Eduardo Zarza Moya (eduardo.zarza@psa.es), www.redcytedestci.org

Funding agency: Programa CYTED. Red Temática Ref.714RT0487

Background: There are many Latin American Countries with good solar resources that could be used to supply a significant fraction of their energy needs. Since Spain has a great experience and know-how about concentrating solar systems and their applications, collaboration between Spain and these countries would be very interesting and of mutual benefit.

Objectives: The dissemination in Latin American countries of the experience and know-how gained by PSA about concentrating solar systems and their applications. The strengthening of scientific collaboration between PSA and R+D groups from these countries, together with the preparation of future joint projects, are included in the objectives.

Results in 2017: ESTCI (www.redcytedestci.org) is a thematic network coordinated by PSA and supported by the Ibero-American Program CYTED (www.cyted.org). 2017 has been the last year of this network. The main result of this thematic network has been the creation of a strong collaboration link amongst all the participating Universities and R+D centres. The main results in 2017 are:

- The design of a hybrid cogeneration solar system (solar thermal + biomass) to produce electricity (100 kWe) and heat (300 kW) has been finished. A small Rankine cycle is used to convert thermal energy delivered by either a solar field composed of small parabolic trough collectors or a biomass boiler. The waste heat of the Rankine cycle at 100ºC may be used to feed any industrial process demanding thermal energy at this temperature level;
- Dissemination and training activities were developed abroad by PSA researchers to explain the basic principles, different technologies, applications and commercial potential of concentrating solar thermal systems. These researchers participated in a 2-day training course and in one-day Seminar with the title "*Sistemas Solares Térmicos de Concentración*" at the city of La Plata (Argentina), on October 3rd to 6th, 2017, and one day workshop at the Universidad del Norte in the city of Barranquilla (Colombia) in September 22nd 2017.

Figure 75. ESTCI Project partners in the final general meeting held at Ciudad de La Plata (Argentina) in October 2017

STANDARDIZATION ACTIVITIES AT BOTH SPANISH AND INTERNATIONAL LEVEL. TECHNICAL COMMITTEES IEC/TC117 AND AEN/CT206

Participants: ABENER, ABENGOA, AENOR, AICIA, CENER, CIEMAT, Iberdrola Ingeniería, PROTERMOSOLAR, SAMCA, Schott Solar, SENER, TECNALIA, TEKNIKER; DLR, Fraunhofer, CEA, ENE, Archimede Solar; IEECAS, LNEG

Contact: Eduardo Zarza Moya (eduardo.zarza@psa.es)

Funding agency: CIEMAT (80%) and European Commission via FP7 ENERGY-2013-IRP Grant Agreement 609.837 (20%)

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.

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

Results in 2017: PSA has participated in all the working groups of the international and national standardization committees IEC/TC-117 and AEN/CTN206/SC117. PSA has also coordinated the working Groups WG1 and WG3 of AEN/CTN206, which have issued two new standards in 2017 (UNE206012 "*Caracterización general de los sistemas the almacenamiento térmico para centrales termosolares con captadores cilindroparabólicos*" and UNE206014 "*Ensayos para la determinación del rendimiento del campo solar de las centrales termosolares con tecnología de captadores cilindroparabólicos*".

PSA has also contributed in the WG2 of AEN/CTN-206 to the development of several standards related to qualification of components for CST systems. Especially important has been the PSA contribution to the standard UNE206016 "*Paneles reflectantes para tecnologías de concentración solar",* which has been finished in 2017 and it will be issued in 2018. This standard includes the testing protocol established to characterize this component, both optically and geometrically, as well as the testing procedures to prove its durability.

In IEC/TC-117, PSA has coordinated the team developing the IEC-62862-1-1 standard on "*Terminology*" for concentrating solar thermal systems, which was finished in 2017 and it will be issued in 2018. PSA has also participated in the following IEC/TC117 standardization groups:

- Project Team 62862-2-1: Thermal energy storage systems - General characterization
- Project Team 62862-3-2: General requirements and test methods for parabolic-trough collectors
- Project Team 62862-3-3: General requirements and test methods for solar receivers
- Project Team 62862-3-1: "Guidelines for design of parabolic trough solar thermal electric plants"

It is also worth mentioning here the coordination of the sub-group of "Reflectance Measurements" of the SolarPACES Task-III by CIEMAT-PSA. This sub-group has been very active during 2017 and its main result was the publication of the updated version of the SolarPACES Reflectance Guideline "*Parameters and method to evaluate the reflectance properties of reflector materials for concentrating solar power tehcnology*. *V3*"

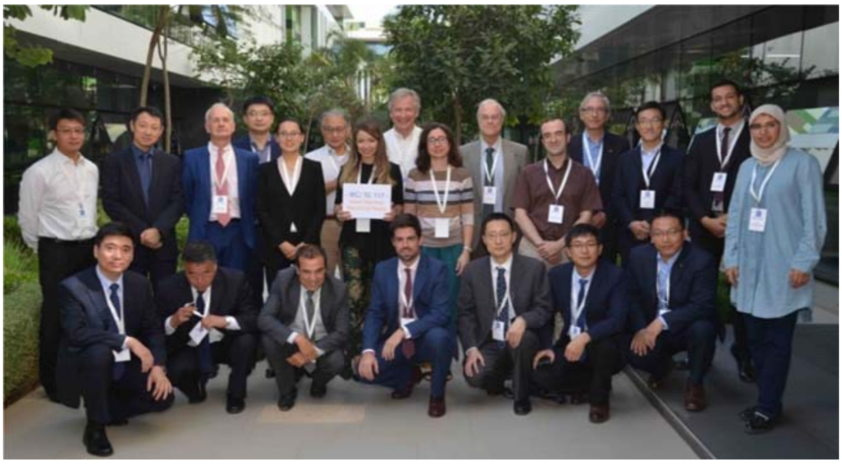


Figure 76. IEC/TC117 General Assembly meeting at Rabat in October 2017, with PSA participation

DETECSOL. Nuevos Desarrollos para una Tecnologia Termosolar mas Eficiente

Participants: CIEMAT

Contacts: Eduardo Zarza (eduardo.zarza@psa.es)

Funding agency: MINECO –Retos Investigación 2014: Proyectos I+D+i (Ref. ENE2014-56079-R) (Jan 2015 – Dec 2018)

Background: Commercial deployment of concentrating solar thermal (CST) technologies has grown significantly. The installed capacity of STE (Solar Thermal Electricity) plants in the World was 354 MWe in 2016, while it is currently of about 5 GWe (2.3 GW in Spain). However, optimization of existing technology and innovative solutions are needed to reduce the installation and O&M costs.

Objectives: The project DETECSOL aims to advance in the development of new components and solutions to improve the efficiency of CST technologies, with the following objectives:

- Study the use of alternative heat transfer fluids (HTFs) in solar receivers
- Performance improvement of solar receivers
- Improve the performance of solar reflectors
- New options for solar thermal energy storage systems.

Achievements in 2017: With regards to the volumetric receiver technology (Task 1.2) a homogeneous equivalent model (HEM), also known as porous media approach, was developed. The coefficients needed for the HEM model were experimentally measured or obtained by means of detailed simulations. This model allows a deep physical insight into the absorbers mechanisms.

In 2017 the thermal durability of a selective coating stable in air up to 700°C has been increased from 500 to 650°C using a double platinum layer that it is stable against thermal diffusion at this temperature (Task 1.3).

The application of antireflective (AR) coatings on quartz windows of central receivers or thermochemical reactors has been also studied, increasing the solar transmittance of glass around 5ppt (Task 1.4). The effect of heating temperature in the AR coating preparation have been investigated, concluding that the coating goes on densifying as the heating temperature increases and that the coating abrasion resistance is remarkably improved when the heating temperature is increased (see Fig. 77).

Regardong durability analysis of solar reflectors in corrosive atmospheres, such as industrial areas (Task 2.2), three reflector materials were subjected to accelerated aging tests which combined a number of environmental parameters, such as temperature, relative humidity, time, and controlled concentrations of the most prevalent air pollutants (H_2S, SO_2 and NO_2), thus obtaining significant results. For instance, the pattern of degradation caused by H_2S in silvered glass reflectors mainly consisted in corrosion spots and clusters, which can reach diameters larger than 700 µm. EDS microanalyses revealed the effective reaction between the sulphurous gas and the metallic parts of the silvered glass reflectors. Conversely, aluminum reflectors did not corrode in the presence of H_2S. As a validation of the selected accelerated parameters, samples were also exposed at five targeted outdoor sites, including oil-refinery and thermal-power-plant environments.

Commercial valves of different configurations and types for molten salt have been tested (Task 3.1). A procedure for evaluating valves packing with much more flexibility (e.g., withouth embeding the packing in the valve) has been designed.

During 2017 several liquid crystals (LC) recommended in the literature as Phase Change Materials (PCMs) have been subjected to thermal cycling (Task 3.3). and all the tested materials degradated. It has been found that having high phase change temperature and enthalpy imply promoting the materials degradation.

Finally, a comparative study was carried out to compare the performance of two 55MW$_e$ solar power plants, one using standard EuroTrough-type collectors and BP/DPO as heat transfer fluid and the second one using larger aperture parabolic-trough collectors with 90mm-∅ receiver tubes and sCO_2 as heat transfer fluid (Task 4.1). Both plants use a thermal energy storage system using molten salts as storage media. The results have been promising in terms of performance and economic potential and this subject will be further investigated.

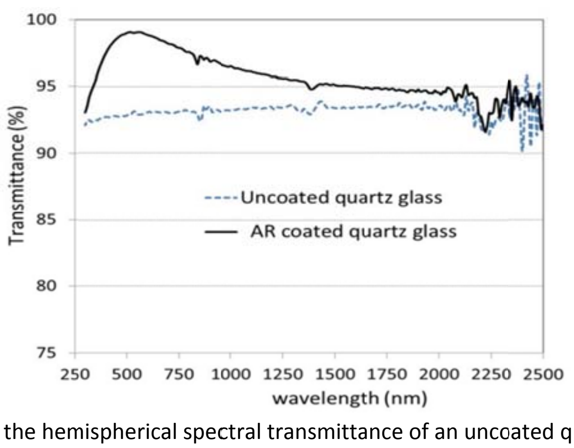


Figure 77. Comparison of the hemispherical spectral transmittance of an uncoated quartz window and a SiO_2 AR coated quartz window.

RAISELIFE. Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology

Participants: DLR, Brightsource, Fraunhofer, CIEMAT-PSA, MASCIR, Dechema, CNRS, Universidad Complutense de Madrid, INTA, Corning, Laterizi Gambetolla (Soltigua), Vallourec.

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

Funding agency: EU-H2020- NMP-16-2015.

Background: The materials of concentrating solar thermal technologies are exposed to harsh outdoor conditions and are targeted to maintain their initial properties. Therefore, one crucial aspect is to improve the practical understanding of long-term in-service degradation on the performance of the functional material and its impact on the overall performance of the technology components and systems.

Objectives: It focuses on extending the in-service lifetime of five key materials for concentrating solar power technologies: 1) protective and anti-soiling coatings of primary reflectors, 2) high-reflective surfaces for heliostats, 3) high-temperature secondary reflectors, 4) receiver coatings for solar towers and line-focus collectors, 5) corrosion resistant high-temperature metals and coatings for steam and molten salts.

Achievements in 2017:

During the second year of the project, CIEMAT-PSA's activities related to the durability analysis of primary reflector coatings (front anti-soiling coatings and back-side paints) were continued. In particular, 8 reflector types were tested outdoor in 9 testing sites including Spain, Morocco, France, Israel and Chile (see Figure 78) and 2 anti-soiling coatings were deeply evaluated under outdoor conditions at the PSA during the whole year. Another activity already accomplished was the design, manufacturing and installation of an outdoor test bench to study the influence of concentrated solar radiation on the durability of the reflectors. Concerning the activities about the durability of high-temperature mirrors for secondary concentrators, the accelerated aging test campaign of the state-of-the-art reflectors sent by the developer (Fraunhofer) was accomplished. Additionally, the solar test bench for the experiments under real concentrated solar radiation at the PSA solar furnace was finished. Within Task 3.5, optical properties of two CIEMAT-PSA's selective absorber have been improved, adding an infrared reflector on the stainless steel substrate. This layer is electroplated chromium that presents higher infrared reflectance and good thermal stability. Solar absorptance is 0.955 in both absorbers and thermal emittance is reduced from 0.13 on stainless steel substrate to 0.09 in chromium coated stainless steel. Thermal durability of both materials was studied and after six months at 400°C there was no degradation in optical properties. Also, the antireflective coatings developed by CIEMAT-PSA for glass covers of solar receivers has been optimized and solar transmittance was increased up to 0.97 and mechanical properties of the coating have been improved too, resulting in a higher resistance to abrasion-erosion degradation. Finally, in relation to the dissemination acitivities (coordinated by CIEMAT-PSA), a workshop was held on 17th of May 2017 at Universidad Complutense de Madrid with the participation of 65 attendees.

Figure 78. Test bench with mirror segments exposed outdoor in Chile.

3.3 MEDIUM CONCRENTATING GROUP

3.3.1 INTRODUCTION

The Medium Concentration group has conducted activities in the field of development, testing, and evaluation of components for line-focus solar collectors (OPAC, DETECSOL and STAGE-STE WP8 projects), testing of a new silicone fluid for parabolic troughs (SITEF project), modeling and simulation of power plants with parabolic-troughs using different heat transfer fluids (DETECSOL and STAGE-STE WP11 projects), water saving technologies for power plants (WASCOP), testing of functional materials (RAISELIFE), and integration of nowcasting methods with simulation models (DNICast project). Besides, this year the participation of the members of the group in different standardization committees (national and international) has continued being relevant and the collaboration with the industry continues in the context of collaboration agreements or technical services.

3.3.2 PROJECTS

OPAC. Optical Characterization and Durability Analysis of Solar Reflectors

Participants: CIEMAT and DLR.

Contacts: Aránzazu Fernández García (arantxa.fernandez@psa.es), Florian Sutter (florian.sutter@dlr.de)

Funding agency: CIEMAT, DLR and customers

Background: One of the key aspects to assure the feasibility of solar concentrating technologies is to achieve suitable solar reflector materials. Proper accelerated ageing tests are needed to predict the durability of solar reflectors under outdoor conditions. Guarantees required for highly efficient components can only be issued after the sucessful application of appropriate standardized testing methods.

Objectives: This collaborative project between CIEMAT-PSA and DLR is devoted to establish appropriate optical qualification and durability test methods of solar reflectors. The degradation processes of solar reflectors are investigated under accelerated aging conditions and in several outdoor exposure sites with the goal of establishing lifetime prediction models.

Achievements in 2017: One of the OPAC priority research lines is to study the effect of sand erosion on the durability of solar reflectors. During 2017, work was done to help solar power plant developers to perform an advanced site assessment in arid locations where the annual irradiance levels are high, but significant quantities of airborne sand and dust increase the risk of optical energy losses due to extinction, soiling, erosion/abrasion damage, etc. Meteorological and geological parameters for sandstorm occurrence and the resulting erosive damage on glass materials by impacting windblown material were extracted from literature. The respective parameters were measured at Zagora and Missour (Morocco). The erosion risk was estimated to be higher in Zagora. The specular reflectance loss of exposed silvered-glass reflectors of 5.9% in Zagora and 0.8% in Missour after 25 months of exposure verified this estimation. A checklist with seven items was prepared to help solar plant developers to evaluate the risk of component aging due to sand storm erosion.

Other research activities have been conducted in the framework of different research projects funded by the Spanish goberment, as DETECSOL, or the European Commission, as STAGE-STE, WASCOP or RAISELIFE. Therefore, details of the achievements in those projects are reported in the corresponding sections included in this annual report.

Technical support and services were also performed in 2017 for several industries, through specific agreements with several companies to evaluate the optical quality and the durability of their products under several accelerated aging conditions in order to assess and improve their performance.

DNICast. Direct Normal Irradiance Nowcasting Methods for Optimized Operation of Concentrating Solar Technologies

Participants: OME, CENER, UniPatras, METEOTEST, ARMINES, RIUUK, SMHI, DLR, TROPOS, CIEMAT, MeteoSwiss, Cyl

Contacts: Lourdes González Martínez (lourdes.gonzalez@ciemat.es)

Funding agency: UE, Seventh Framework Programme. EU-7FP- ENERGY.2013.2.9.2. Grant agreement no: 608623. (Oct. 2013 – Sept 2017).

Background: The efficient operation of concentrating solar technologies (CSTs) requires reliable forecasts of the incident irradiance for two main reasons: (i) for better management of the thermodynamic cycle, as it becomes possible to dynamically fine tune some of its parameters (flow rate of HTF or the defocusing mirrors), (ii) because electricity production can be optimally connected to the grid.

Objectives: The main objective is to establish a portfolio of innovative methods for the nowcast of DNI and to combine these methods, validate the nowcasts and assess the influence of improvement in DNI nowcasting on nowcasting of concentrating solar power (CSP) and concentrating photovoltaic (CPV) power plants output. The PSA has been participating in the work packages 2 and 4, the first devoted to define prerequisites for nowcasting method development and the second dedicated to perform validation of the nowcasting methods and analyse plan output nowcasting.

Achievements of the project: The work of PSA-Ciemat in this project has been in two work packages. In the WP2 a comprehensive report on the requirements of nowcasting systems for Concentrating Solar Technologies (CST) has been compiled by DLR and CIEMAT. The **report (D2.1)** was completed in March 2014 and presented at the **First End User Workshop held in Madrid on May 7th, 2014** and at the **DNICast project meeting held in Paris on July 10th and 11th, 2014**. The result of this work was also presented by Tobias Hirsch from DLR in the **SolarPaces 2015 conference** that took place in Cape Town, South Africa (13-16 October).

Since the solar plant outputs are in relation with the incoming solar energy, the nowcasted DNI will be combined with plant performance models to allow the nowcasting of the plant output. In the WP4 a 35 MWel parabolic trough simulation plant model with Eurotrough 100 parabolic-trough collectors, water as heat transfer fluid and without storage has been developed. The optimization of the CSP production depends on the solar irradiation, and the operation strategy has to be focused on the solar field control that is more sensitive to differences in solar radiation along the field area. The results of this work package were compiled by DLR and CIEMAT in the **report D4.4**: "Nowcasting of CST plant output WP 4.3 CST plant simulation and yield production nowcast" in June 8th. The main conclutions were presented in the **Third end-user workshop held on June 1st, 2017** at the occasion of the **Intersolar Europe Exhibition in Munich** and in the **2017 EMS Annual Meeting - European Conference for Applied Meteorology and Climatology** that was organized from 4 to 8 September 2017 at the Helix, Dublin City University, Ireland.

SITEF. Silicone Fluid Test Facility

Participants: DLR (coordinator), CIEMAT, Wacker Chemie AG, TSK Flagsol Engineering GmbH, Senior Flexonics GmbH, TÜV NORD SysTec GmbH & Co. KG

Contacts: Loreto Valenzuela (loreto.valenzuela@psa.es); Christoph Hilgert (christoph.hilgert@dlr.de)

Funding agencies: Solar-ERA.NET Transnational Call CSP 2 2014; MINECO – Retos 2014 Acciones de programación Conjunta Internacional (Ref. PCIN-2014-083) (Jan 2015-Dec 2016); German Federal Ministry of Economy and Energy and German Federal Ministry of Innovations, Science and Research (Jan 2016-Dec 2017)

Background: Silicone based heat transfer fluids (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®). SHTFs are pumpable below 0°C, environmental-friendly, low in hydrogen formation, almost odourless and very low in acute toxicity. Until now, such fluids are not used in large-scale commercial CSP power plants because available SHTFs are currently far more expensive than the widely used eutectic mixture of diphenyl oxide and biphenyl (DPO/BP). The development, testing and demonstration of reliability, performance, and competitiveness of new SHTFs are of great interest of the CSP sector.

Objectives: The SITEF (Silicone fluid Test Facility) project aims to demonstrate the loop scale functionality and applicability of a new Wacker Chemie AG silicone heat transfer fluid named HELISOL®5A and associated parabolic-trough solar collector (PTC) components 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 efficien.cy. This innovate project is based on a German-Spanish cooperation making use of the so called PROMETEO test facility located at Plataforma solar de Almería (PSA).

Achievements in 2017: During this year the PROMETEO pilot plant has been operated with the new SHTF HELISOL® 5A manufactured and supplied by Wacker Chemie AG in the solar collectors. At the end of December there were accumulated more than 300 hours of operation at outlet fluid temperatures above 400°C and up to 425°C (see Fig. 79). During this last year of project, the main goal has been to accumulate operational hours at high temperature and get operational experience with the new fluid in terms of examining the adequate working pressure in the circuit, continuous sampling of the fluid to monitor the quality of the fluid during the continuous heating/cooling in the circuit, performance of the solar field components, etc. No major problems have been noticed.

To continue the study and experimental analysis of new silicone fluids, during this year a new Solar-ERA.NET project was submitted and approved. The new project, called SIMON, will start officially in 2018 and will have as objective to continue the demonstration of HELISOL® fluids in parabolic-trough collectors.

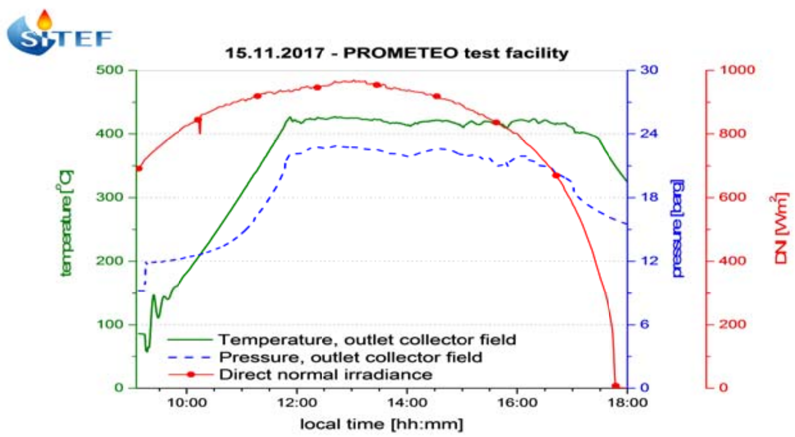


Figure 79. SITEF project: Experimental data during early operation of PROMETEO test facility with Helisol®5A.

3.3.3 GROUP STAFF PHOTO

a)

b)

Figure 80. Medium Concentration Group staff working a) at Plataforma Solar de Almería in Tabernas (Almería) and b) at CIEMAT Headquarters in Madrid.

3.4 HIGH CONCENTRATING GROUP

3.4.1 INTRODUCTION

As a remarkable fact in 2017, and a great practical result of the PRESOL project, an atmospheric extinction measurement system has been implemented at the PSA, being the first system that offers an online measurement of this extinction. This is of vital importance in the design, planning and operation of central receiver systems.

At the same time, in addition to continuing our activities in the projects already started in previous years, it has marked the beginning of the NEXTOWER project, financed by the European Commission in its H2020 programme. Project focused on the development of materials for volumetric air receivers connected with liquid metals heat storage. This project is one of the first examples of collaboration between the research communities in the fields of concentrating solar and nuclear power, where many crosscutting actions and knowledge can be shared between each other.

3.4.2 PROJECTS

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

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

Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es); Antonio Ávila-Marín (antonio.avila@ciemat.es)

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

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

Objectives: NEXTOWER project aims at demonstrating high-performance durable materials for the next generation of concentrated solar power (CSP) air-based tower systems, making them commercially competitive in the energy market beyond 2020. 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.

Results in 2017: The activities carried out this year have focused on the design of a small power prototype (200kWth) consisting of an atmospheric volumetric receiver coupled to a liquid lead storage tank. This device is planned to be installed in the Plataforma Solar de Almería during 2018 in order to test the concept and its operation at temperatures of up to 700^{O}C.

In parallel to the design of the test loop, work is being carried out on the development of metallic materials compatible with liquid lead at high temperatures; and on new geometries, designs and coatings for ceramic volumetric absorbers that increase both their thermal performance and durability.

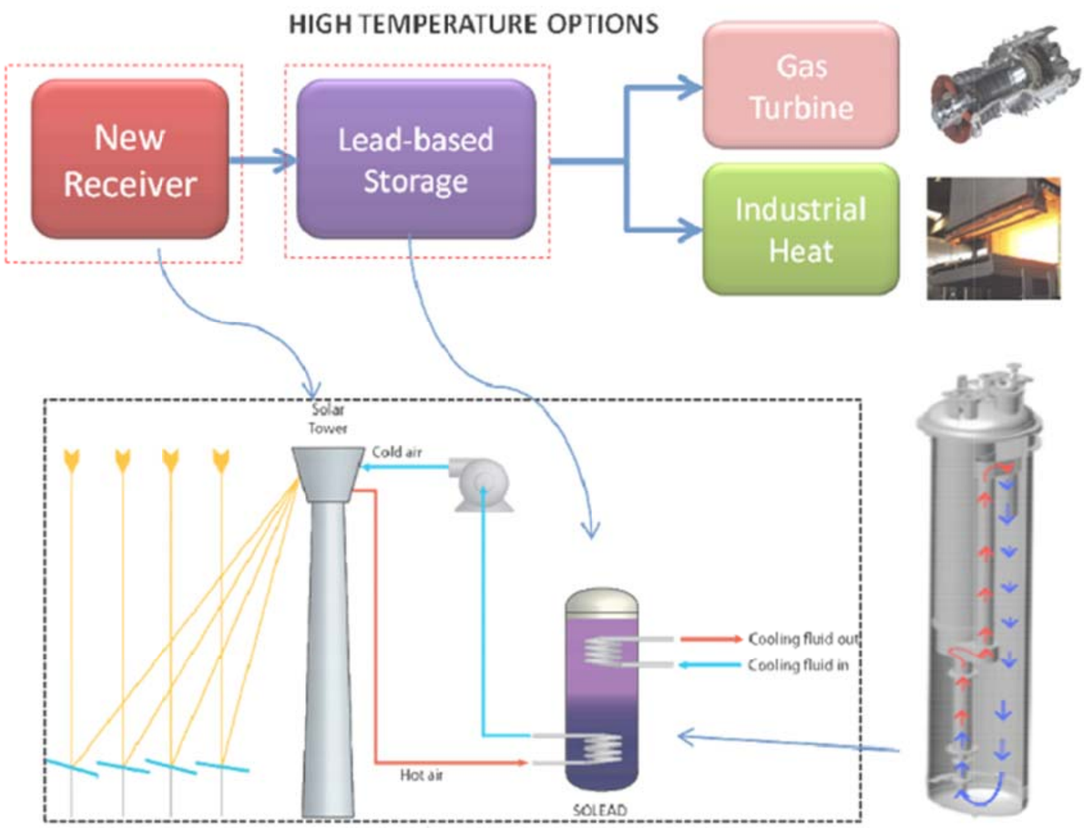


Figure 81. Scheme of the objectives NEXTOWER will pretend to fulfil with the development of the project.

CAPTURE. Competitive Solar Power Towers

Participants: CENER (Coordinator), TEKNIKER, CIEMAT-PSA, FRAUNHÖFER-IKTS, BLUEBOX ENERGY LTD, CEA, FCT GMBH, SONCEBOZ SA, HAVER&BOECKER, TSK FLAGSOL, K-CONTROLS LTD, EDF, EUREC EESV.

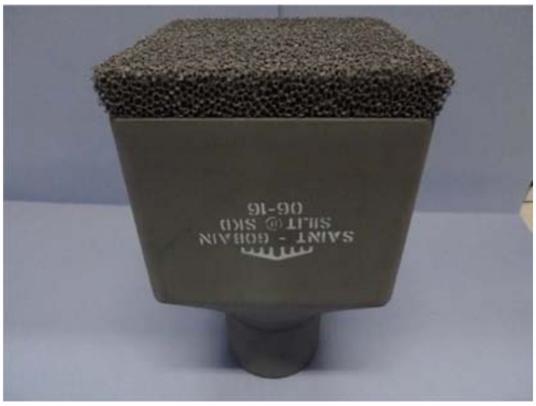
Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es); Antonio Ávila-Marín (antonio.avila@ciemat.es)

Funding agency: European Commission, H2020-LCE-2014-2015

Background: Volumetric atmospheric air receiver technology is a promising alternative to increase receiver efficiency of Solar Tower Power Plants. CIEMAT-PSA works on this technology since 1990 testing more than 15 different volumetric receiver prototypes in the las 20 years; being a strategic technology field of High Concentration Solar Group.

Objectives: The project global objective is to increase plant efficiencies and reduce levelized cost of electricity by developing all relevant components that allow implementing an innovative plant configuration consisting on a multi-tower decoupled advanced solar combined cycle approach that not only increases cycle efficiencies but also avoids frequent transients and inefficient partial loads, thus maximizing overall efficiency, reliability as well as dispatchability; all of which are important factors directly related to cost competitiveness on the power market.

Results in 2017: The activity carried out during year 2017 in the Capture project was focused in the experimental evaluation of two volumetric solar absorbers concepts (Figure 82). A comparison of the thermal performance of conventional foam absorbers with an innovative rotary disc absorber design was performed. The absorbers have been tested at cup-level at an experimental air loop installed at a parabolic dish (PD) concentrator at PSA. From the previous test performed in the solar simulator (during 2016), the best foams were selected to further analysis on a cup level. In addition, a test bed to test four cups at PSA solar tower has been set up for the final evaluation of the three selected foams selected after PD tests.



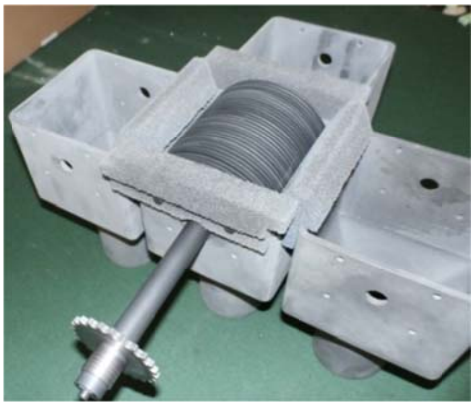


Figure 82. Foams absorber on cup level (left) and rotary disc on cup lever (right)

ALCCONES. Storage and conversion of concentrating solar power

Participants: IMDEA Energía-UPAT (Coordinator), CIEMAT-PSA, URJC-GIQASOL, CSIC-IPCPA, SENER, AH, EA.

Contacts: Jesús Fernández-Reche (jesus.fernandez@psa.es); Antonio Ávila-Marín (antonio.avila@ciemat.es)

Funding agency: Comunidad de Madrid, S2013/MAE-12985

Background: During the last years, concentrating solar power has been the renewable energy with the highest year-on-year growth rate. Nevertheless, the technology used up to now reaches 18-20% of nominal performance in the conversion of solar radiation to electricity and the investment cost of solar thermal electricity plants is still high. Therefore, it is required to improve the efficiency of their thermal conversion processes and turn solar energy into a dispatchable one by the integration of thermal storage systems.

Objectives: CIEMAT's participation is focused on: i) analysing the behaviour of innovative thermal fluids to achieve higher working temperatures and developing a better integration with more efficient thermodynamic cycles; ii) improving solar receiver designs to work more efficiently at high temperatures and solar irradiance.

Results in 2017:

CIEMAT-PSA performed an exhaustive study of graded porosity concept during first years of the project, and then a numerical computational fluid dynamics (CFD) approach was set up. For that purpose, the first step was the numerical analysis of the heat transfer coefficient (HTC) between the air flow and six detailed staggered stacked plain-weave wire mesh screens, the second is to produce correlations of the HTC. Finally, the CFD approach was compared and validated with experimental results. Figure 83 shows the local volumetric HTC and the Nusselt number of one of the meshes studied compared with literature data.

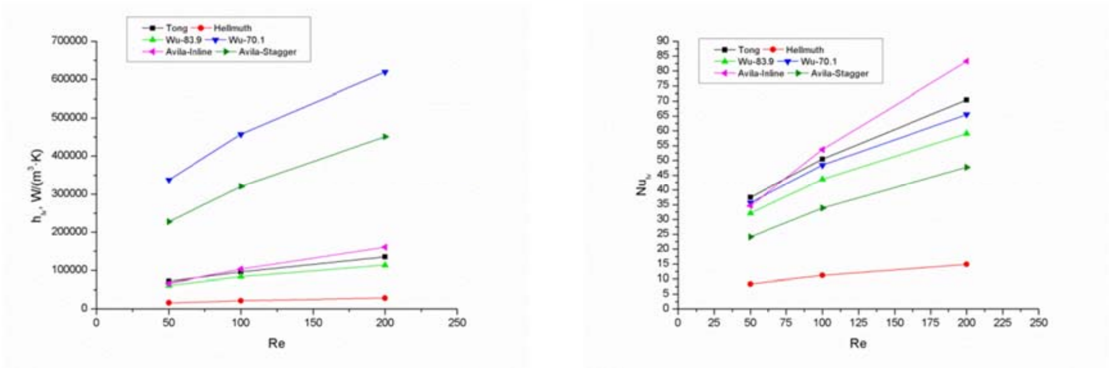


Figure 83. Local volumetric heat transfer coefficient comparison (left) and local volumetric Nusselt number comparison (right)

Concerning the sensible heat storage work package, during the year 2017, CIEMAT-PSA carried out several tests with the objective of analyzes the isolation of the thermal energy storage tank without filler material. The main goal of this work is to get the conduction coefficients of the tank based on experiments rather than using theoretical correlations for further implementation in CFD tools. 84 depict the conduction coefficient for different working temperatures.

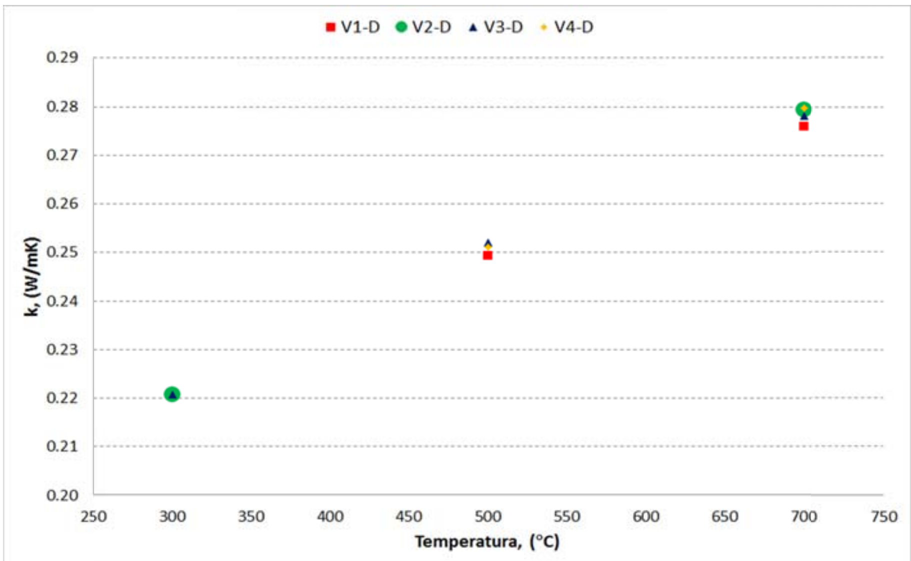


Figure 84. Isolation conductivity as function of the working temperature

PRESOL. Forecast of Solar Radiation at the Receiver of a Solar Power Tower

Participants: CIEMAT-PSA, Almería University, Huelva University.

Contacts: Jesús Ballestrín (jesus.ballestrin@psa.es)

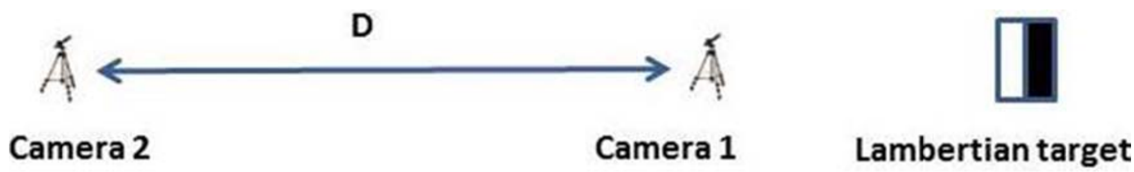
Funding agency: This research has been funded by the Spanish government in the framework of the PRESOL project (Ref. ENE2014-59454-C3-3-R) with ERDF funds.

Background: Power generation from Solar Power Towers (SPT) -where DNI is a critical input- is experiencing a rapid growth worldwide. The greater challenge posed by these large solar installations is the grid integration. To this end, it is crucial to have an accurate forecast of the DNI levels reaching the receiver, which affects not only the plant operation but the energy price market.

Objectives: The project goal is to produce a short-term forecast of the DNI reaching the SPT receiver. To this end, we propose to forecast the DNI arriving to the heliostat field and develop techniques to determine and forecast the reflected solar radiation attenuation on its path to the receiver.

Results in 2017: Atmospheric extinction of solar radiation reflected by heliostats to receiver is recognized as an important cause of energy loss in the increasingly large solar tower plants. During the design of these plants would be desirable extinction maps similar to those of direct normal irradiance. Unfortunately, the reality is that there is currently no reliable measurement method for this quantity and at present these plants are designed, built and operated without knowing this local parameter.

Nowadays, digital cameras are used in many scientific applications due to their ability to convert available light into digital images. Their broad spectral range, high resolution and high signal to noise ratio, make them an interesting device for extinction measurement. A novel measurement system for solar extinction at ground level based on two digital cameras and a Lambertian target has been developed. The first experimental results show that the system can measure solar extinction in the bandwidth 400-1000 nm with an accuracy of less than an absolute ±2%. This measurement system is currently running on a daily basis at Plataforma Solar de Almería.



FIGURE

Figure 85. Digital cameras take images of the target

3.4.3 GROUP STAFF PHOTO

Figure 86. High Concentration Group Staff working at the Plataforma Solar de Almería (left) and CIEMAT-Madrid (right)

3.5 SOLAR FUELS / SOLARISATION OF INDUSTRIAL PROCESSES GROUP

3.5.1 INTRODUCTION

Solar Thermal Electricity (STE) is a very promising renewable source of energy. The best known application so far is bulk electricity generation through thermodynamic cycles, but other applications have also been demonstrated, such as production of hydrogen and high temperature solar heat production.

The lines of activity are concentrated in the following fields:

- Development of hybrid solar/fossil endothermic processes with special attention to low quality carbonaceous materials.
- Pre-commercial scale demonstration of the technical and economic feasibility of water splitting for hydrogen production through the use of thermochemical cycles with concentrated solar energy.
- Technological feasibility of the use of solar thermal energy as the energy supply in high temperature industrial processes.

3.5.2 PROJECTS

HYDROSOL. Thermochemical HYDROgen production in a SOLar monolithic reactor: construction and operation of a 1MW PLANT

Participants: APTL (Greece), DLR (Germany),), Hygear (Netherlands), HELPIRES (Greece) and CIEMAT-PSA (Spain).

Contacts: Athanasios G. Konstandopoulos [agk@cperi.certh.gr] Alfonso Vidal, alfonso.vidal@ciemat.es

Funding: 2.5 M€; FCH-JU-2012.

Duration: January 1, 2014 - April 30, 2018

Background: The principal objective of HYDROSOL-PLANT is the development and demonstration operation of a plant for solar thermo-chemical hydrogen production from water in a 750 kW scale on a solar tower, based on the HYDROSOL technology.

Objectives: Based on the above, the specific Scientific and Technical Objectives of the work proposed within HYDROSOL-PLANT are the following: construct a solar hydrogen production demonstration plant in the 750 kW range to verify the developed technologies for solar thermochemical H_2O splitting. Operate the plant and demonstrate hydrogen production and storage on site (at levels > 3 kg/week) [1]. Finally, the proposal is directed to perform a detailed techno-economic study for the commercial exploitation of the solar process.

Achievements in 2017: During 2017, the pilot plant was commissioned. The HYDROSOL-Plant is completed and ready for operation. The receiver-reactor combined with the rest of the peripheral components, including steam generators, preheaters, reactor arrays, etc. have been placed on 1st floor. The 2nd floor will accommodate equipment for separation and purification stages on the process (PSA, tanks, etc.).

Fig. 87.a. Photograph of the reactor array

Fig. 87.b. Final plant configuration

After completion of the plant, a hazard and operability study (HAZOP) was prepared that provides the basis for the development of system control schemes, allowing for further safety and operational investigations.

A preliminary thermal testing campaign is ready to be performed. Special emphasis will be put on the temperature level achieved, on the dynamic behavior, on potential temperature gradients, and on the active volume of the absorbers. High temperature gradients may lead to local hot spots and consequently failure of the receiver. The temperature distribution can be controlled by defining several aiming points on the receiver surface and adjusting the heliostats accordingly.

Having established all necessary conditions and adjustments for temperature uniformity, the hydrogen production step will be initiated. The temperature levels, mass flows, duration of reaction steps will be applied together with the special solar coupling providing alternating solar flux and the process control system.

The core of this evaluation will be the quantitative assessment of the campaigns vs. the objectives set and current state-of-the-art figures according to the proposal goals: reactor efficiency (thermal and chemical), hydrogen Production Rate 1400ºC: ≥ 3 kg/week, etc.

HITERSOL. Clean technologies for solar hydrogen production based on mixed-ferrites thermochemical cycle.

Participants: ABENGOA Hydrogen (company subsidiary of the ABENGOA group) and CIEMAT

Contacts: M. Maynar, maria.maynar@abengoahidrogeno.com;

Aurelio Gonzalez, aurelioj@psa.es

Funding: 150 k€; CTA-IDEA.

Duration: June 1, 2014 – December 31, 2015

Background: Some high temperature endothermic reactions for converting solar energy to chemical fuels have been investigated around the world. Many of the activities to this point dealt with identifying, developing, and assessing improved receiver/reactors for efficient running of thermochemical processes for the production of H_2. A challenging approach is investigated at the Hitersol project where the reactor used to drive the ferrites cycle is a cavity receiver using tubular reactors.

Objectives: HITERSOL is cooperation between CIEMAT-PSA, and the company Abengoa Hydrogen, established within the framework of CTA-IDEA Initiative funded by the Andalusia Community.

Hitersol pursued to develop clean technologies for solar hydrogen production based on water splitting by mixed-ferrites thermochemical cycle. To achieve this aim, an installation was designed, constructed and commissioning within a previous project named SolH2. Present collaboration pursued to complete the evaluation of a 200 kW pilot plant erected in PSA.

Achievements in 2017: During the first part of the INNPACTO project, the pilot plant was commissioned and tested. The multi-tubular solar reactor was tested during the SolH2 project period and confirms that the proposed technology meets the hydrogen production targets. Chemical tests were carried out and some results are obtained regarding H_2 production at different operating conditions with different temperatures (800 to 1200 ºC) and N_2/steam mass flow ratios.

Along 2016 some additional tests were addressed to operation of a plant with solar transients. Then a comparison of the experimental tests and CFD results for this multi-tubular solar reactor for hydrogen production was performed in collaboration with the University of Seville.

CFD simulations allow to solve the thermal balance in the reactor (cavity and tubes) and to calculate the percentage of reacting media inside the tubes which achieve the required temperature for the process.

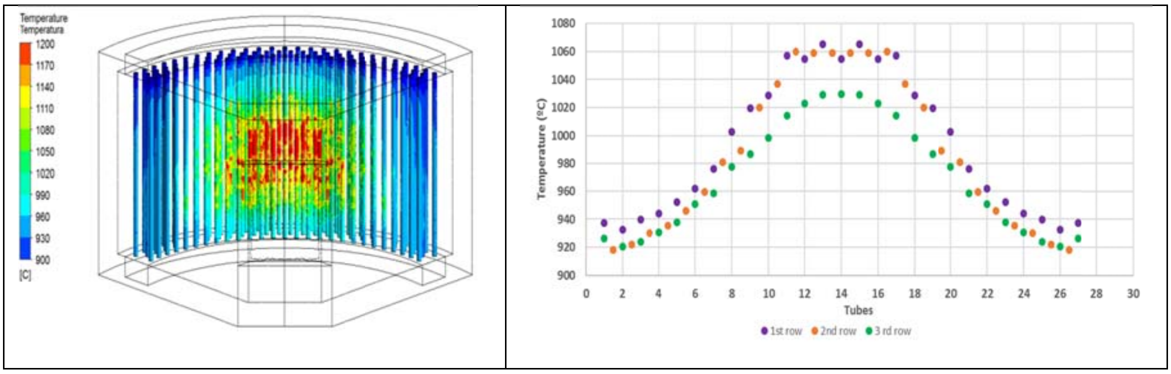


Figure 88. (a) Temperature distribution of CFD simulations. (b) Average temperature in the tube surfaces distribution.

An operation strategy previously performed by ray tracing simulations was applied to supply the required power with the optimal flux distribution onto the alumina tubes.

The CFD model is used for the calculation of the temperature and radiation flux profiles at the cavity and receiver walls, and has been validated based on the results of the thermal testing campaign. In addition, the temperature distribution inside the tubes is calculated in order to analyze how homogenous it is and whether the required temperature is achieved [1].

ALCONNES. Storage and Conversion of concentrated thermal solar energy

Participants: IMDEA Energia (Coordinator), University J. Carlos I, ICP-CSIC and CIEMAT. SENER (Spanish engineering company) and ABENGOA Hidrógeno (company subsidiary of the ABENGOA group) act as industrial companies with active collaboration and interest in the possible exploitation of the project results.

Contacts: Manuel Romero, manuel.romero@imdea.org; Alfonso Vidal, alfonso.vidal@ciemat.es

Funding: 2,017 M€; Community of Madrid.

Duration: October 1, 2014 – October 31, 2017

Background: The ALCONNES project is a very ambitious initiative that involves R&D public institutions, IMDEA Energia (Coordinator), University J. Carlos I, ICP-CSIC and CIEMAT. The program AlCConES (the acronym in Spanish stands for Storage and Conversion of Concentrated Solar Power) focuses its R&D objectives onto the heart of CSP systems, that is the loop involving conversion from high flux solar to thermal energy, including the storage system needed to optimized dispatch on demand for further use of energy in the production of electricity, solar fuels or chemicals.

Within objective 2, CIEMAT is exploring new solar receivers and reactors for the efficient operation at high temperatures and with high penetration of photons for high incident flux. Furthermore, within objective 3, “Develop new storage and dispatching thermal energy systems”. CIEMAT will be focused on new perovskite materials as candidates for thermochemical cycles.

Achievements in 2017:

Some work in 2017 was focused to study the technical feasibility of chemical reactors concepts based on direct heated fluidised bed reactors Commercial Ni ferrite were selected as a model material for solar experiments.

CIEMAT has continued working in optimizing the operating conditions while IMDEA has designed and assembled a laboratory test bed using a "beam-down" type chemical reactor for the analysis of the reducing step of non-volatile metal oxides. Tests were performed using N2 as fluidization gas. For CIEMAT, the goal of this study is to improve the understanding of fluidized bed hydrodynamics by determining the effects of bed height and minimum fluidization velocity, this value is found 2.3 cm/s for air and 1.9 cm/s for argon.

Within objective 3, our research efforts were directed towards preparation and synthesis of the perovskites materials in the laboratory, improving the kinetics and reducing the working temperatures.

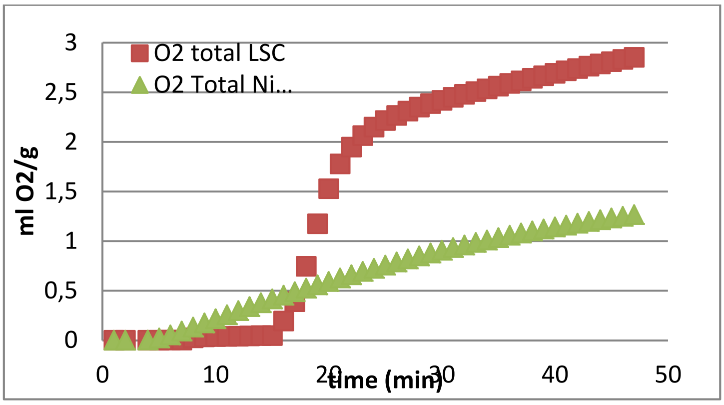


Fig. 89. Oxygen released on the regeneration step from $NiFe_2O_4$ and LSC samples.

First hydrolysis test carried out with these materials in a thermogravimetric analyser indicated with $La_{0.5}Sr_{0.5}CoO_3$ and $La_xSr_{1-x}Fe_yAl_{1-y}O_3$ that they are good candidates for further tests (Fig. 3). First hydrolysis test carried out with this material indicated both (a) oxygen release in perovskite materials is higher than Nickel ferrites (fig. 88) (b) hydrogen production is lower than the expected one according to the oxygen released in the reduction step. Furthermore, the oxygen released in the reduction step was decreased in each consecutive cycle showing that cobalt perovskite is not a stable material.

RESPACE. Subproject 3. Methodology and characterization of materials and components for receivers for solar applications under extreme conditions

Participants: IMDEA Energia (Coordinator), Centro de Investigación en Nanomateriales y Nanotecnología (CINN) and CIEMAT.

Contacts: Manuel Romero, manuel.romero@imdea.org;
Alfonso Vidal, alfonso.vidal@ciemat.es

Funding: 180 k€ (Subproject 3); Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad, en el marco del Plan estatal de Investigación Científica y Técnica y de Innovación 2013-2016. Ref. ENE2015-71254-C3-2-R.

Duration: January 1, 2016 – December 31, 2018.

Background: The research program ARROPAR-CEX proposes a multidisciplinary analysis on novel concepts of indirectly heated receivers/particle reactors for solar applications under extreme conditions. Extreme operating conditions are understood to be those which involve the combination of high irradiance, in excess of 1000 kW/m^2, and very high temperatures, typically above 800 °C.

ARROPAR-CEX is divided into three sub-projects in order to achieve significant advancements in several scientific and technological knowledge areas, which together will lead to the development and subsequent commercial deployment of new devices, materials and methodologies in concentrating solar thermal energy, responding to the "Safe, Efficient and Clean Energy" challenge of the Spanish Strategy for Science, Technology and Innovation: Within objective 2, CIEMAT will study new multifunctional ceramic materials for solar applications under extreme conditions, focusing on the development of ceramic components that are adapted to operating conditions beyond the current state-of-the-art.

For this, the development of novel multifunctional composite materials is envisaged, which will enhance the stability of the component under pressure/vacuum at high temperatures and reduce its losses by thermal emission. Thermochemical processes require thermally and chemically stable reactor wall materials, which can withstand severe operating conditions suitable for specific solar fuels production. Reactor materials of construction comprising walls, the cavity lining, insulation, and shell need to fulfill the thermal and chemical requirements of severe operating conditions at high temperatures and under high-flux solar radiation.

Achievements in 2017:

For such purpose, we focus on AlN, SiC, and Al_2O_3. These materials were subjected to thermal treatment in air, steam, and ageing tests to determine the optimal material for each specific application.

A set of tests has to be defined and carried out in order to depict some degradation of selected materials to be used as reactor walls under specified conditions similar to those foreseen in actual solar chemical reactors.

During 2017, CIEMAT performed cyclic oxidation tests with samples from CNRS (SiC fibre reinforced SiC) and LNEG (CeO_2) in a tubular electric furnace. (Figure 89).

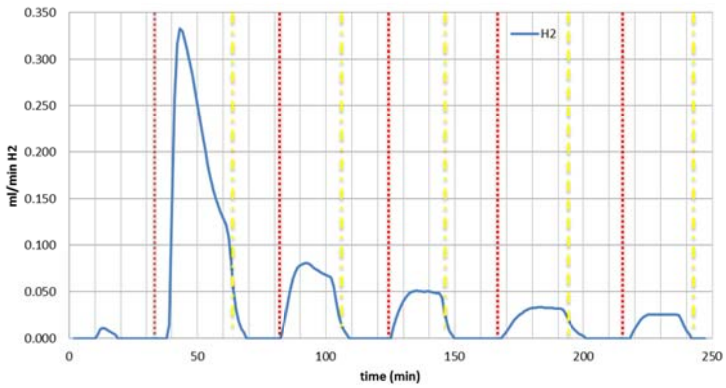


Fig. 90. Left: H_2 evolution during cycling of SiC/SiC$_f$ (1200°C in Ar, 1000°C in Ar + steam

These studies show that an initial rapid oxidation occurs at 1200 ºC when steam is introduced into the furnace, resulting in an abrupt initial peak of the hydrogen being released. As is shown hydrogen concentration profile exhibit a maximum at the beginning and a gradual decay to zero when steam flow is switched off. Upon a second, third and so on after steam injection, smaller peaks are observed. This behaviour could show some kind of stabilization, indicating the formation of a layer (SiO_2) which protects the substrate.

ORESOL. Release of Oxygen from Lunar Regolite using concentrated solar energy

Participants: CIEMAT-PSA (Spain).

Contacts: Thorsten Denk; thorsten.denk@psa.es

Funding agency: European Commission 6th Framework Programme ERA-STAR Regions (ERA – Space Technologies Applications & Research for the Regions and Medium-Sized Countries - CA-515793- ERA-STAR REGIONS), ESP2007-29981-E.

Background: The project Oresol originates from the "ERA-STAR Regions" program, where it was part of a joint initiative between Andalusia and Bremen/Germany. PSA continued the activity due to the unique possibility to investigate a promising type of solar chemical reactor for reactions that need the processing of large quantities of solids.

Objectives: The principal goal of the project is the development and testing of a solar powered fluidized bed reactor for the extraction of oxygen from lunar regolith. This is done by the reduction of one constituent of lunar soil, ilmenite ($FeTiO_3$), with hydrogen, and the subsequent electrolysis of the obtained water.

Achievements in 2017:

An extensive solar testing campaign was performed in winter and spring 2017 with a total of 26 solar tests. In the first phase, the system was operated with atmospheric air, without chemical reaction, and the temperature in the bed was limited to 400°C to avoid damage on graphite parts. The goals of the five tests of this “Phase 1” were to learn to know in depth the behavior of the fluidized bed with the particles, to check the proper functioning of most of the peripheral components, to hone the data acquisition and control program, to confirm the initial predictions of the gas demand of the bed in function of the temperature, and finally to establish efficient procedures to pass as fast as possible through the low temperature part of the heating process. The latter one is of special practical importance because this is where the gas consumption is highest, and hence determining the cost of the tests when argon is used.

The six tests of “Phase 2”, with pure argon, were to determine the operation parameters (temperatures, gas flows and pressures, solar power), and to demonstrate the ability of the system to reach the minimum nominal operation temperature of 800°C. Additional tests helped to understand the behaviour of the system with continuous particles in- and outflow, with a special interest on the variation of the solar power demand.

Finally, in “Phase 3”, hydrogen was added to the system and the temperature further increased. Fifteen tests were performed, eleven of them with hydrogen, two for particle flow / solar power tests, and two for TV interviews. The basic goal here was to demonstrate that the reaction really occurs. Further objectives were to gain initial information about the water quality, and, as a bonus, to calculate the hydrogen conversion rate.

All primary testing objectives were accomplished. The basic operation parameters, especially the main fluidized bed gas flow, were determined. Continuous particle feed and removal was demonstrated. A maximum bed temperature of 977°C was achieved. The desired chemical reaction was carried out, converting more than 50% of the hydrogen into water with the oxygen being extracted from the ilmenite mineral. It arose during the tests that the system is also able to extract very efficiently the crystallization water in the minerals, thereby making it suitable for water extraction on Mars.

Fig. 91. Oresol experiment with hot particles on the test platform of the Solar Furnace SF60

A proposal (named ALCHEMIST) has been presented within the European Space Agency (ESA) Invitation To Tender AO-9107: Study for ESA for a payload testing lunar regolith reduction with hydrogen on the Moon to be flown not later than 2025. Thanks to the experience with Oresol, Ciemat was able to win the Call. ALCHEMIST aims to set a solid scientific and technological basis for the first feasible approach of oxygen (O_2) production from regolith on the Moon.

3.5.3 GROUP STAFF PHOTO

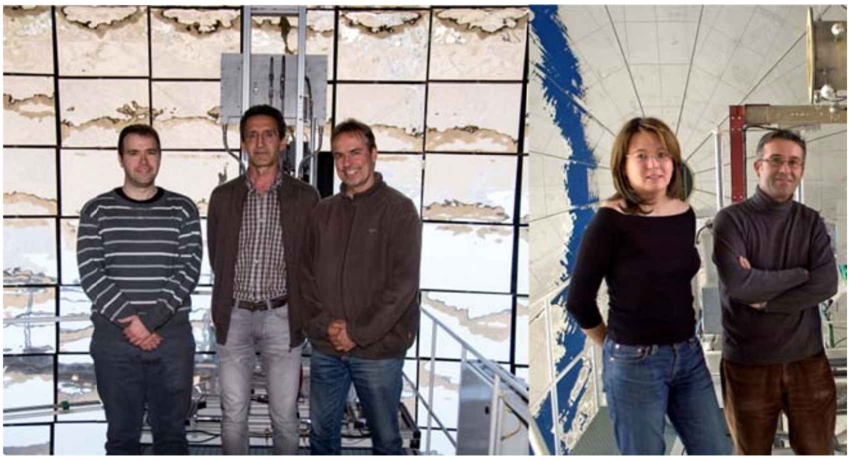


Figure 92. Staff of the Solar Fuels/Solarisation of Industrial Processes Group.

3.6 THERMAL STORAGE GROUP

3.6.1 INTRODUCTION

The technical activities in 2017 have been focussed on studying the feasibility of storage media, testing components for molten salt loops (valves, pressure gauges) and modelling the behaviour of Thermal Energy Storage Systems (TESS).

3.6.2 PROJECTS

REELCOOP. Research Cooperation in Renewable Energy Technologies for Electricity (2013-2018)

Participants: UPORTO (coordinator), UoR, DLR, UoE, CIEMAT, ENIT, IRESEN, YU, ONYX, MCG, Termo, Sol, ZE, AES, CDER.

Contacts: Esther Rojas (esther.rojas@ciemat.es)

Funding Agency: EU-FP7-ENERGY.2013.2.9.1

Background: REELCOOP was conceived with the aim to develop renewable electricity generation technologies and promoting cooperation between EU and Mediterranean Countries, in order to change the fact that today still 17% of the world population has no access to electricity, with 2/3 living in rural areas of Africa and Asia.

Objectives: Three prototypes for renewables are going to be developed, constructed and tested:

Prototype#1: building integrated PV system (with ventilated facades),
Prototype#2: hybrid (solar/biomass) micro-cogeneration ORC system, and
Prototype#3: hybrid concentrating solar/biomass mini-power plant[1].
A special effort is made to transfer and disseminate the developed technologies.

Results in 2017: The main contribution of CIEMAT/PAS is the development of an, already patented, own design of thermal storage for latent heat with low-thermal conductivity phase change materials. In spite of its relatively low phase change enthalpy, the chosen PCM was Hitec salt since it was the only PCM out of the 9 PCM that does not degrade under cycling. Due to budget limitations for manufacturing a specific prototype with the design proposed for this project, a commercial spiral heat exchanger has been modified accordingly. The experimental results[2] obtained for this prototype have showed that the proposed solution is not as promising as expected. Additionally, the lack of appropriate testing methods for validating long term behaviour of PCMs has been identified.

[1] SolarPACEs2017, SolarPACEs2017, Willwerth, L.; Rodriguez-García, M.M., Rojas, E., Ben Cheikh, R.; Ferchichi, S.; Jmili, A.; Baba, A.; Soares, J.; Parise, F.; Weinzierl, B., Krüger, D.; Commissioning and Tests of a Mini CSP Plant.

[2] SWC 2017 / SHC 2017, Rodriguez-Garcia, M. M; Rojas, E., Test Campaign and Performance Evaluation of a Spiral Latent Storage Module with Hitec® as PCM.

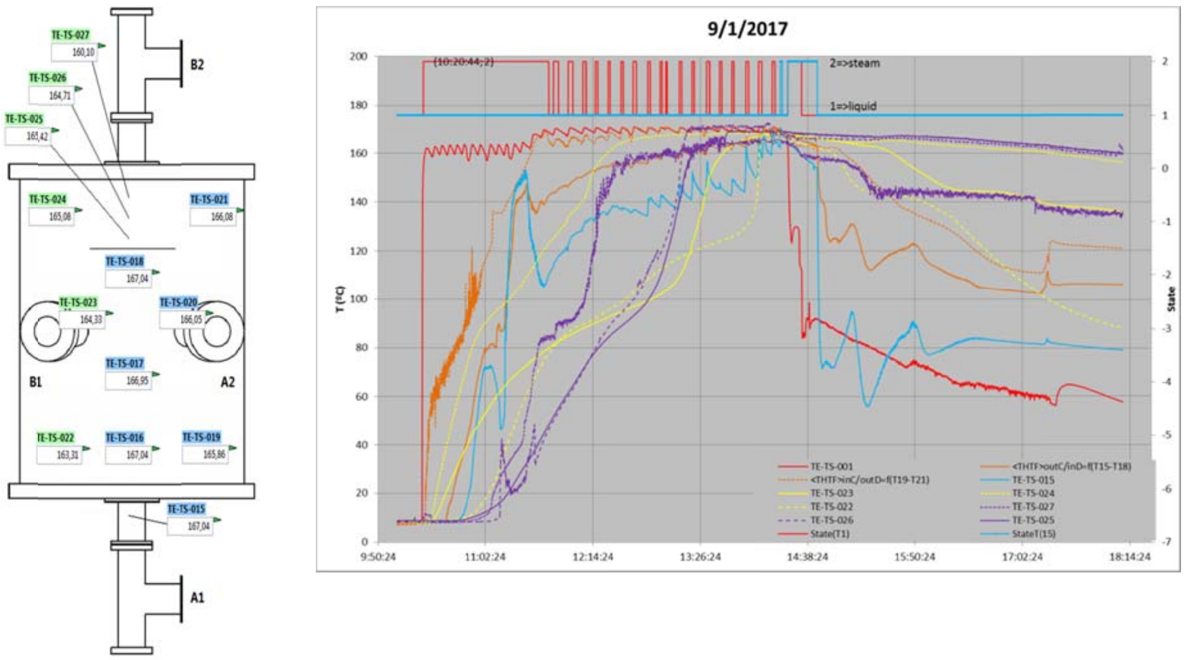


Fig. 93. REELCOOP storage prototype experimental data

3.6.3 GROUP STAFF PHOTO

Figure 94. Thermal Storage Group staff

4. SOLAR DESALINATION UNIT

4.1 INTRODUCTION

The Solar Desalination Unit (UDeS in its Spanish acronym) has the objective of new scientific and technological knowledge development in the field of desalination and thermal separation processes powered by solar energy.

Main current research lines are the following:

- Large-capacity thermal processes with special emphasis in multi-effect distillation (LT-MED, TVC-MED, ABS-MED)
- Small-capacity thermal processes with special emphasis in membrane distillation (MD) and forward osmosis (FO)
- Co-generation of electricity and desalinated water (CSP+D)
- Salinity-gradient power generation: reverse electrodialysis (RED) and pressure-retarded osmosis (PRO)
- Thermal-driven separation processes for brine concentration and industrial waste water treatment
- Dynamic modeling, process optimization and advanced control strategies in solar desalination processes.

During 2017, the PSA Solar Desalination Unit has continued with its relevant activity in the field of solar thermal desalination. The joint organization, together with the European Desalination Society (EDS), of a yearly course about solar desalination is a proof of this reference position. Likewise, this year has led to the consolidation of the research activity “Dynamic modeling, process optimization and advanced control strategies in solar desalination processes”, by officially incorporating three new researchers (two PhD & one pre-doctoral) to the unit team.

New developments in MED (metal-doped plastic heat exchangers) and MD (new generation of spiral-wound air-gap modules) have been tested at PSA experimental facilities showing a promising future for these thermal-powered desalination technologies.

The international relevance of the developed activities is clearly supported by the following positions currently held by the unit:

- Member of the European Desalination Society (EDS) Board of Directors (2016-2018)
- Coordination of the Renewable Energy and Desalination Working Group of the European Water Platform (WssTP)
- Coordination of the Renewable Energy Desalination Action Group of the European Innovation Partnership on Water of the European Commission.
- Operating Agent of SolarPACES (Solar Power and Chemical Energy Systems) Task VI (Solar Energy and Water Processes and Applications).

During 2017 research activities were developed within the framework of projects covering both national and international activities with academic and industrial involvement.

4.2 PROJECTS

ZCR2. Zero Carbon Resorts towards Sustainable Development of the Tourism Sector in the Philippines and Thailand

Participants: Gruppe Angepaste Technologie GrAT (AT) (coordinator), Palawan Council for Sustainable Development PCSD (PH), Green Leaf Foundation GLF (TH), Health Public Policy Foundation HPPF (TH), CIEMAT-PSA (ES)

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

Funding agency: European Commission, SWITCH-Asia Programme.

Background: This project builds upon the success and achievements of the ZCR in the Philippines (2009-2014) for replication and upscaling. Regional approach will be implemented through ZCR intervention in Thailand and Green Certification in the Philippines, while increasing the access to green finance and improving policy exchanges on SCP in tourism in both countries.

Objectives: The overall objective of this project is to contribute to sustainable development of the tourism sector and its value chain in the Philippines and Thailand with a focus on reduction of resource consumption and CO_2 emissions.

Achievements in 2017: During this year, CIEMAT-PSA supported the development of a Green Certification Scheme for tourist resorts. Our main work, however, was on the publication of results from the evaluation of commercial modules of membrane distillation for decentralized, solar-powered seawater desalination, and also its combination with solar oxidation techniques for wastewater decontamination. Also, a solar water disinfection system for a stand-alone application was designed, with the intention of replicating in Palawan's ZCR demonstrator.

RED-Heat-to-Power. Conversion of Low Grade Heat to Power through closed loop Reverse Electro-Dialysis

Participants: WIP (D) (coordinator), UNIVERSITY OF PALERMO (IT), FUJIFILM (NL), REDSTACK (NL), CIEMAT-PSA (ES), UNIVERSITY OF EDINBURGH (UK), UNIVERSITAT POLITECNICA DE CATALUNYA (ES)

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

Funding agency: European Commission, Horizon 2020 programme

Background: The concept is based on the generation of electricity from salinity gradient using Reverse Electrodialysis with artificial saline solutions operating in a closed-loop. The original salinity gradient is regenerated by a separation step that uses heat at 40 – 100 °C.

Objectives: The overall objective is to prove this revolutionary concept, develop the necessary materials, components and know-how for bringing it to the level of a lab prototype generating electricity from low-grade heat at higher efficiencies and lower costs than ever achieved to date. The specific objective of CIEMAT-PSA is to select the most suitable technologies for the regeneration process and the combinations of salts and solvents that can maximise the system performance.

Achievements in 2017: CIEMAT-PSA has evaluated a novel vacuum-enhanced air-gap configuration for increased performance of membrane distillation. Laboratory tests confirmed the results of simulations, with improvements between 30-40%. Also, the pilot plant for combining reverse electrodialysis and membrane distillation as a thermal regeneration system was built at PSA. The MD is based on spiral-wound modules able to work in air-gap and vacuum-enhanced air-gap configurations.

Figure 95. Pilot-plant for assessment of combined reverse electrodialysis and membrane distillation

STAGE-STE. Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy – WP10: Solar Thermal Electricity + Desalination

Participants: CIEMAT-PSA (WP10 coordinator) (ES), FISE (DE), ENEA (IT), CEA (FR), CYI (CY), LNEG (PT), CENER (ES), UEVORA (PT), UNIPA (IT), SENER (ES), HITTITE (TR), FBK (IT)

Contact: Dr. Diego-César Alarcón-Padilla (diego.alarcon@psa.es)

Funding agency: European Commission, IRP 7th FP

Background: Combined electricity and fresh water production by means of solar thermal concentrating technologies can be proposed as a solution in many locations of the world where water scarcity usually coincides with the availability of high solar irradiation levels.

Objectives: The main objective of STAGE-STE WP10 (STE+Desalination) is to answer the basic question about under which conditions a solar thermal cogeneration scheme can be more feasible than the separate production of power by a STE plant and the use of such power to run a desalination process.

Achievements in 2017: During this year techno-economic analysis of the different CSP+D thermal cogeneration schemes have been completed and the results have been compared with the independent generation of electricity and fresh water using reverse osmosis. The results have shown that, except in geographic locations with extreme conditions for the use of membranes, thermal desalination technologies need to increase their energy efficiency and reduce their investment costs in order to be competitive.

EFFERDESAL. Subproject title: Efficient energy control and management of solar thermal desalination systems

Participants: UAL (ES) (ENERPRO) , CIEMAT-PSA (EFFERDESAL)

Contacts: Dr. Diego-César Alarcón-Padilla, diego.alarcon@psa.es

Funding agency: Ministerio de Economía y Competitividad, Plan Estatal. I+D+i 2013-2016 orientada a los retos de la sociedad.

Background: Due to increasing demand -for energy and water, most countries are promoting the efficient use of these resources to reduce costs and increase sustainability. Generally, energy efficiency is not only associated with technological improvements, but also with the improvement of control and energy management. This is the main framework of this research project ENERPRO, which is a natural evolution of a previous project, POWER, where both UAL and CIEMAT-PSA subprojects focused on heat/cooling and water management.

Objectives: The main objectives of the subproject are:

1. Dynamic modeling of solar-gas hybrid desalination plants.
2. Analysis of energy storage systems and auxiliary systems for energy cost reduction.

3. Design of simplified models for control purposes.
4. Development of MPC strategies for desalination plants.
5. Coupling of solar desalination plants to supply water to greenhouses and buildings.
6. Testing of control algorithms both in simulation and in the real installations.

Achievements in 2017: During this year, the following relevant results have been obtained:

1. A hierarchical controller has been tested at the solar membrane distillation (SMD) facility based on a model predictive controller (MPC) that optimizes the operation under different criteria (distillate, specific thermal consumption and electrical costs).
2. An MPC hierarchical controller has been proposed in a SMD system to reduce the specific thermal consumption assuring a distillate volume for greenhouse irrigation.
3. Experimental characterization of the MED unit (performance ratio and distillate production) at different operating points.
4. Analysis of the optimal operating conditions of a MED unit and a double-effect absorption heat pump under energetic and exergetic criteria.
5. An experimental campaign at the SMD facility has been carried out to train a neural network and characterize SolarSpring's membrane distillation modules.
6. Development of a dynamic model of a parabolic trough solar field of small concentration ratio.
7. Characterization of the apparent delay in a field of stationary flat plate collectors.
8. Development of dynamic models for heat storage systems.

REWACEM. Resource recovery from industrial waste water by cutting edge membrane technologies

Participants: FRAUNHOFER INSTITUTE (coordinator) (DE), AEE INTEC (AT), BFI (DE), UNIPA (IT), CIEMAT-PSA (ES), DEUTSCHE EDELSTAHLWERKE (DE), SOLARSPRING (DE), AT&S (AT), ELECTRONIQUEL (ES), DEUKUM (DE), AIZ (AT), USTUTT (DE), TECNOZINCO (IT), PSE (DE)

Contact: Dr. Guillermo Zaragoza (guillermo.zaragoza@psa.es)

Funding agency: European Commission, H2020 Program

Background: Production of metal goods brings, along with the generation of a multitude of different wastewater streams as the ones from cooling circuits and gas cleaning, rinsing water and diluted pickling acids from electroplating as well as washing water from casting of tools and automotive components. The high demand of water, often needed in demineralized quality for rinsing or washing purposes, is already a problem for production sites in the semi-arid regions of Southern Europe. Additionally, metal processing consumes plenty of different process fluids like acids, bases, and salts leading to contaminated wastewater streams, which need disposal causing high costs and significant environmental impact in general.

Objectives: The main objective of REWACEM Project is the application and demonstration of innovative and efficient water treatment technologies with the effect of a significant reduction of water use, waste water production, chemical consumption and energy use for the metal production, processing and coating industries. The proposed approach is an integrated system comprising between one and two cutting edge membrane technologies (Diffusion Dialysis (DD) and Membrane Distillation (MD)) which is highly suitable for adaptation to the manifold metal processing branches using low grade waste heat and concentration gradients to provide energy efficient waste water treatment and liquid stream recovery.

Achievements in 2017: During this year, the pilot plant for its application in the production process of the project partner ELECTRONIQUEL was designed. It will recover copper and sulphuric acid from their copper electroplating line, using a combination of membrane distillation and diffusion dialysis. The components of the plant were defined and agreed with all partners in order to use similar elements in the four pilot plants to be constructed.

NESTER. Network for Excellence in Solar Thermal Energy Research

Participants: CYI (coordinator) (CY), CIEMAT-PSA (ES), ENEA-UTRINN (IT), CNRS-PROMES (FR), RWTH-AACHEN (DE)

Contact: Dr. Diego Alarcón (diego.alarcon@psa.es)

Funding agency: European Commission, H2020 Program

Background: The geopolitical placement of Cyprus offers excellent opportunities for cultivating a research and innovation niche in solar technologies. At the same time the remoteness of the corresponding centres of Excellence of EU is a major impediment. The NESTER Project strives to enhance the advantages and ameliorate the disadvantages of this geographical placement.

Objectives: The NESTER Project aims in upgrading the scientific and innovation performance of the Cyprus Institute (CyI) in the field of Solar-Thermal Energy. The upgrade will be achieved by embedding the Institute's activities in a network of excellence, which will provide access to the latest know-how and facilities, train CyI's scientific and technical personnel and link it with the European Industry. The substantial investments made/planned by CyI in infrastructure and personnel will thus become more efficient and competitive allowing claim to international excellence.

Achievements in 2017: During this second year of the project the most remarkable activities have been the collaboration in the organization of winter schools, specific workshops, secondments and mentoring visits.

4.3 UNIT STAFF PHOTO

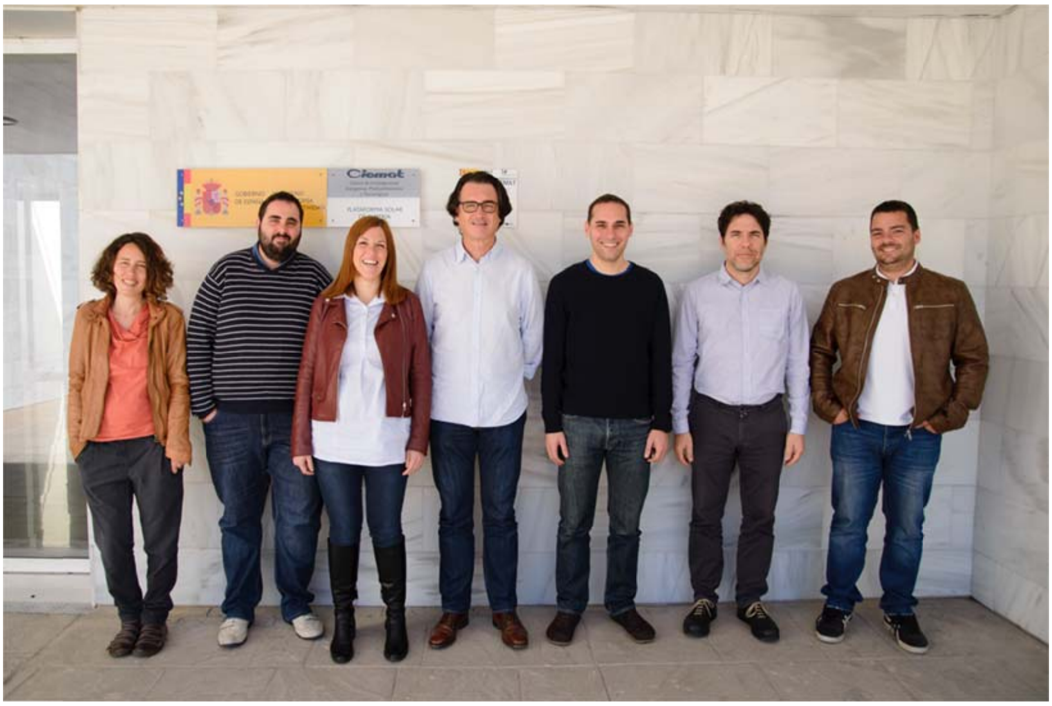


Figure 96. Members of the UDeS Unit

5. SOLAR TREATMENT OF WATER UNIT

5.1 INTRODUCTION

The main objective of the Research Unit of Solar Treatment of Water 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 25 years of research activity. The group has been involved in almost all the international projects related to the development of solar photocatalytic water treatment plants through the FP4, FP5, FP6, FP7 EU and H2020 program, within the topics of environment, material sciences, chemical engineering, chemistry and microbiology. We are also pioneers in the use of advanced analytical techniques for the evaluation of advanced oxidation treatments. Nowadays, several R&D projects are running in collaboration with different International Institutes and Universities. The research activities already consolidated by this unit are the following, cross-linked with the projects and networks summarised in the following pages:

- Solar photocatalytic and photochemical processes as tertiary treatment of wastewater for the removal of pollutants of emerging concern and microorganisms, related with **NEREUS** and **PHOTOCAT** networks, **WATER4CROP** project and **AQUALITY** Marie Skłodowska-Curie Action.

- Solar photochemical processes for the remediation of industrial wastewaters containing biorecalcitrant compounds (pharmaceuticals, pesticides, landfill leachates, textile and wine industry), related with **TRICERATOPS** project.
- Integration of Advanced Oxidation Processes with other water treatment technologies (NF/UF; Ozone, Bioprocesses, etc.) for improving efficiency and reducing costs, related with **TRICERATOPS** project and **AQUALITY** Marie Skłodowska-Curie Action.
- Evaluating photocatalytic efficiency of new materials under solar light in pilot reactors, related with **FOTOFUEL** network and **HIDROPILSOL** project.
- Photocatalytic and photochemical processes for water disinfection in different scenarios (different wastewaters and drinking water including resistant pathogens), related with **WATERSPOUTT** project and **ALICE** Marie Skłodowska-Curie Action.
- Pilot solar photo-reactors for production of hydrogen and other photo-fuels, related with **FOTOFUEL** network and **HIDROPILSOL** project.

5.2 PROJECTS

FOTOFUEL. New Challenges in Solar Fuels production

Participants: IMDEA Energía (Coord.), CIEMAT-PSA, ICP-CSIC, UPV-CSIC (ITQ), IMDEA Materiales, Institut Catala de Investigacio Quimica, Laboratorio de Luz de Sincrotrón (ALBA-CELLS), UB, UJI, Instituto de Investigación en Energía de Cataluña (IREC)

Contacts: Dr. S. Malato Rodriguez; sixto.malato@psa.es

Funding agency: Spanish Ministry of Economy and Competitiveness, Network of Excellence (Reference ENE2016-82025-REDT)

Background: According to the IEA report from the COP21 meeting, it will be necessary to reduce emissions by 40-70 % in order to limit the global temperature increase to 2ºC with respect to preindustrial values. This will imply an investment of 13.5 trillion $ in energy efficiency and low carbon technologies. In this frame, solar fuels, produced from abundant feedstocks (CO2, H2O) and using sunlight as renewable source, represent one of the most promising alternatives to fossil ones.

Objectives: The goal of FOTOFUEL is to significantly advance the development of materials and devices for efficient solar fuels production. With that purpose, synergies and network collaboration will be promoted among the main research groups in this field, providing them, at the same time, with a platform for international exposure.

Results in 2017: Network of excellence. The scientific program involves four research lines: (i) Design and synthesis of advanced multifunctional materials, (ii) Development of theoretical and experimental characterisation tools, (iii) Design and set-up of efficient photoreactors and devices and (iv) Process viability and standardisation. Former FOTOFUEL network (2015-16) meant the ideal frame in order to exploit existing links and promote new ones. The present network intends to settle and reinforce such cooperation and to place the Network in the international scene, creating the seed for a future European network on solar fuels. See: http://fotofuel.org/

FOTOCAT. New photocatalytic materials and reactors for removal of micropollutants and pathogens

Participants: Universitat Rovira i Virgili–URV (Coord.), PSA-CIEMAT, UEX, URL, UAL/CIESOL, ICRA, UPV, URJC

Contacts: Dr. M. Ignacio Maldonado; mignacio.maldonado@psa.es

Funding agency: Spanish Ministry of Economy and Competitiveness, Network of Excellence (Reference CTM2015-71054-REDT)

Background: To achieve a sustainable use of water resources, it is necessary to increase the volume of reclaimed water. To obtain an effluent of suitable quality for the different uses permitted for reclaimed water it is necessary to reduce the content of pathogens and persistent organic pollutants. This could be achieved through the proper development of photocatalytic processes.

Objectives: The aim of the FOTOCAT network is to achieve a significant progress in the development of materials and photocatalytic reaction systems for the treatment and reuse of wastewater. The research groups that comprise the FOTOCAT network have altogether a wide experience in the synthesis of new catalytic materials, photocatalytic reactor design and implementation of these processes for the treatment and reuse of wastewater, allowing them to face the challenges identified for their industrial application. The various actions planned to be undertaken will contribute to the training of new researchers in the application of photocatalytic processes for water treatment and reuse and the need for its sustainable use.

Results in 2017: Network of excellence. The work is based on scientific collaboration and joint implementation of a work program based on cutting-edge research, information, dissemination and communication and technology transfer. Along 2017 two short stays within the funding of FOTOCAT have been carried out. First, Dra. Inmaculada Polo from the Solar Water Treatment of Unit at CIEMAT-PSA spent two weeks (from the 11th to the 22nd of September 2017) in the Universidad Rey Juan Carlos, collaborating with Dr. Javier Marugán in the analysis and discussion of previously obtained results in other scientific and technical activities carried out within other common projects. Secondly, the researcher Sandra Yurani Toledo, from the Universiad Rovira I Virgili, came from the 9th to the 27th of October 2017 to the PSA for training activities in the operation and control of the hydrogen generation pilot plant available at the facilities of the Solar Treatment of Water Unit. See: http://fotocat.es/

NEREUS. New and emerging challenges and opportunities in wastewater reuse

Participants: 336 participants from 40 countries (EU and associated countries). NIREAS-International Water Research Center (Cyprus), coord. CIEMAT-PSA is member of managing committee and co-coordinates Working Group 4.

Contacts: Dr. S. Malato Rodriguez; sixto.malato@psa.es

Funding agency: European Cooperation in Science and Technology, H2020- Cost Action (ES1403)

Background: Treated urban wastewater is currently widely reused to compensate for dwindling water supplies, as it is considered to be a reliable alternative water source. Several knowledge gaps associated with wastewater reuse still exist, including: (a) accumulation of metals/elements in the soil and their subsequent uptake by plants and crops, (b) fate of organic microcontaminants in downstream environments, and (c) epidemiological potential of antibiotic resistant bacteria and/or resistance genes (ARB&ARG) discharged from treated effluent. Contamination of the environment, the food chain, drinking water, etc with ARB&ARG is presently considered to be a serious public health problem.

Objectives: The Action intends to (i) deliver best-practice recommendations to wastewater reuse in irrigation, (ii) develop uniform means for assessing wastewater quality with respect to contaminants of emerging concern and also ARB&ARG, (iii) establish specifications for technologies able to produce wastewater with minimal levels of such contaminants, and (iv) compile valid and reliable information to be used in regulatory frameworks.

Results in 2017: The work is based on scientific collaboration and joint implementation of a work program. Two meetings (in Patras and Vienne) have been organised. WG 4 (coordinated by PSA) has organised a Summer School in Porto and has recently finished all the deliverables related with its activity. From such deliverables as reference, two different review papers are in progress to be published in high IF journals. See http://www.nereus-cost.eu/

WATER4CROP. Reducing the water cycle demand in vegetables process industry by novel water treatment: reuse for vegetables washing and agricultural reuse

Participants: CIEMAT-PSA; Universidad Rey Juan Carlos (coordinator).

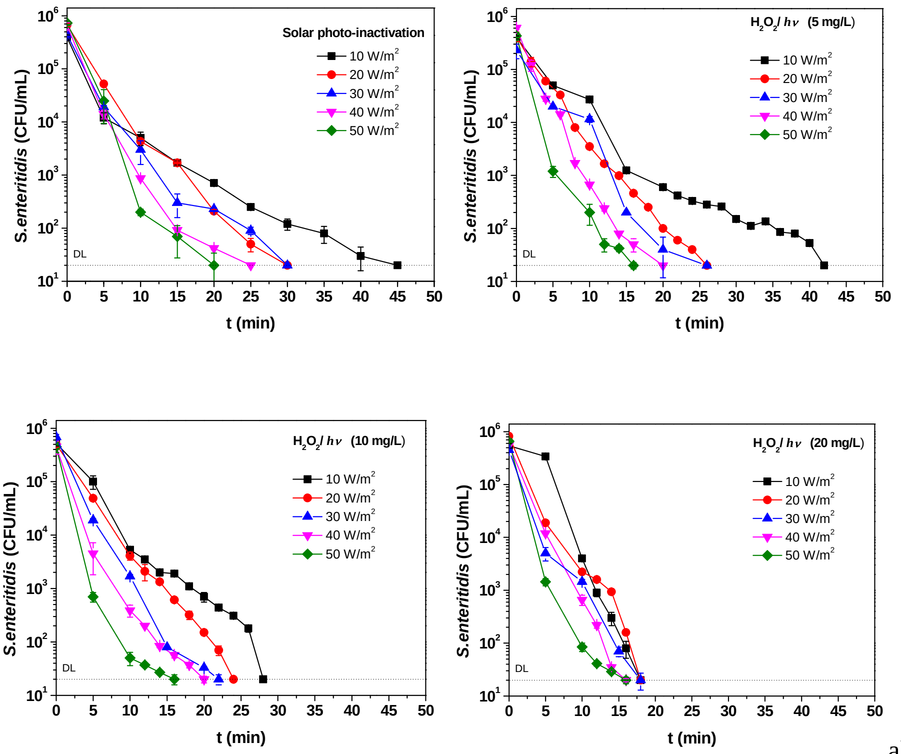
Contacts: Dr. M. Inmaculada Polo López, inmaculada.polo@psa.es

Funding agency: Spanish Ministry of Economy and Competitiveness (Reference CTQ2014-54563-C3-3-R).

Background: To explore different ways to save fresh water, like the reuse of industrial wastewater effluents for agriculture but they should be previously treated. Advanced Oxidation Processes have demonstrated to be a promising treatment to enhance the wastewater effluents quality, reducing the presence of emerging pollutants (chemical and biological) to regulated limits (RD 1620/2007).

Objectives: The main objective is the assessment of several Advanced Oxidation Processes (O_3/H_2O_2, solar photo-Fenton, H_2O_2/solar radiation) for the treatment of fresh-cut industry wastewater (FCWW) contaminated with E. coli O157:H7, Salmonella and a cocktail of pesticides in pilot reactors and further reuse for raw-eaten crops irrigation in an experimental greenhouse.

Results in 2017: i) Study of the optical and energy limitations between solar photons and H_2O_2 over the inactivation of E. coli and Salmonella enteritidis under controlled conditions in a solar simulator and using synthetic fresh-cut WW. The influence of UVA irradiance (10–50 W/m^2) on the inactivation of both pathogens at several H_2O_2 concentrations was investigated (Figure 95.a). ii) The capability of a commercial iron fertilizer commonly employed to remediate the iron chlorosis in agriculture has been investigated as alternative source of iron for photo-Fenton processes. Inactivation rates were compared with other solar processes; iii) Assessment of the simultaneous degradation of pesticides and inactivation of both bacteria at pilot scale by several Advanced Oxidation Processes: ozonation and solar process (H_2O_2/Solar and photo-Fenton) within a flow 60L-CPC solar reactor (Figure 95.b). iv) Finally, the assessment of the chemical and microbiological fate of the pollutants investigated in this work has been conducted in irrigated crops. Lettuce and radish crops were irrigated with mineral water (as negative control) and synthetic fresh-cut WW polluted with both bacteria and pesticides. After 1.5 and 3 months of growth and regular irrigation, leaves, products and soil were harvested and analysed using different analytical techniques. Crops cultivation was conducted under controlled conditions of temperature and humidity (Figure 95.b).



a)

b)

Figure 97. a) *S. enteritidis* abatement by solar photo-inactivation and H_2O_2/solar with 5 mg/L, 10 mg/L and 20 mg/L at several solar UVA irradiances under controlled conditions. b) Pilot plants located at PSA facilities and used for disinfection and decontamination assays of synthetic fresh-cut WW, from left to right: ozonation pilot plant, solar CPC reactor and crop camera.

WATERSPOUTT. Water Sustainable Point of Use Treatment Technologies

Participants: CIEMAT-PSA; Universidad Rey Juan Carlos; University of Strathclyde; University of Malawi; Ecole Polytechnique Federale de Lausanne, National University of Ireland Maynooth, Makerere University; Stellenbosch University; Ecosystem Environmental Services S.A.; Mekelle University; Buckinghamshire New University; Helioz gmbh; Dublin City University; Stichting IHE Delft; Universidad de Santiago de Compostela; Royal College of Surgeons in Ireland (coordinator).

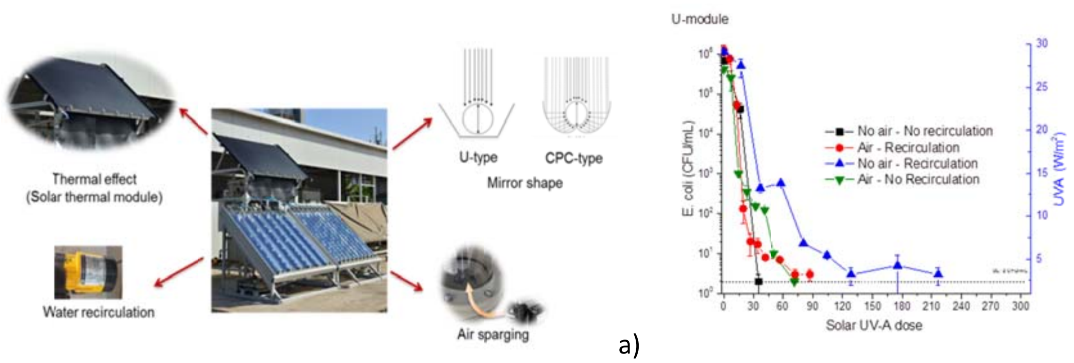
Contacts: Dr. M. Inmaculada Polo López, inmaculada.polo@psa.es

Funding agency: European Commision. Horizon 2020. H2020-WATER-2014-2015/H2020-WATER-2015-two-stage.

Background: In 2015 nearly 660 million people remain without access to safe drinking water in rural areas. Solar water disinfection (SODIS) is a household water treatment that uses solar energy to inactivate pathogens in water stored in transparent containers. Nevertheless, some limitations are still affecting the efficiency and acceptability of this process by users.

Objectives: To increase the user uptake of SODIS by bringing to market novel solar based technologies providing larger volumes (≥20L) of treated water per day in each household. CIEMAT objective is to develop new reactors for disinfection of harvested rainwater providing 125 liters/day. The final reactor will be evaluated in South Africa and Uganda.

Results in 2017: Several physical parameters affecting SODIS efficiency in the two new concepts of SODIS-reactor have been assessed, i.e, the influence of mild-heat temperatures driven by solar heating (T range 25-55 ºC), air injection (using air spargers in the reactor), water recirculation as opposite to static batch systems, and the influence of mirror shape on solar water disinfection efficiency (CPC-type versus U-type Aluminum reflectors) (Figure 96.a). The assessment of the solar reactor has been tested under controlled conditions using a microbial consortium of waterborne pathogens commonly present in harvested rainwater (E. coli, Enterococcus, phage MS2, Salmonella, Pseudomonas and Cryptosporidium) and using a synthetic rainwater formula adapted from literature. Best operational conditions found for the higher inactivation rate were obtained with U-type mirror, without air sparging and no recirculation (Figure 96.b). Based on these results, 4 field prototypes (2 for Uganda and 2 for South Africa) have been built by Ecosystem S.A. and tested at PSA facilities. Two different tube diameters and total number of tubes were used in those prototypes, 100 mm (6 tubes) and 200 mm (3 tubes) for 90 and 140 L reactor, respectively (figure 96.d). See also: http://www.waterspoutt.eu/



a) b)


c)

d)

Figure 98. a) Imagen of SODIS-based prototype remarking the physical parameters that will be assessed during solar disinfection of synthetic rainwater. b) Inactivation of *E. coli* obtained in the SODIS-based prototype under different operational conditions. c) 90L solar reactor for and d) 140L solar reactor for South Africa at PSA facilities.

HIDROPILSOL. Fundamental and solar pilot plant scale studies of photocatalytic hydrogen production with simultaneous removal of water pollutants

Participants: CIEMAT-PSA

Contacts: Dr. M. Ignacio Maldonado; mignacio.maldonado@psa.es

Funding agency: Spanish Ministry of Economy and Competitiveness (Reference CTQ2013-47103-R)

Background: The present project is intended to deepen into the knowledge of the heterogeneous photocatalytic processes for the production of hydrogen gas from water and wastewater containing organic contaminants, at pre-industrial solar pilot plant scale.

Objectives: (i) To determine the semiconductor "composite" that yields a larger efficiency of hydrogen generation; (ii) To carry out the scale-up from laboratory to solar pilot plant; (iii) To perform mechanistic studies of the process.

Results in 2016: A Cu/TiO_2 photocatalyst has been synthesised by reducing a Cu precursor with $NaBH_4$ onto the surface of a sulphate pretreated TiO_2 obtained by a sol-gel procedure. The catalyst, that shows a clearly defined anatase phase with high crystallinity and relatively high surface area, and contains Cu_2O and CuO deposited on its surface, has been used to produce hydrogen in a solar driven pilot plant scale photocatalytic reactor at PSA. Different electron donor aqueous solutions (methanol, glycerol, and a real municipal wastewater treatment plant influent) have been tested showing similar or even higher energy efficiency than those obtained using more expensive noble metal based photocatalytic systems. The glycerol solutions have provided the best reactive environments for hydrogen generation. Figure 97 shows best H_2 productions for the different sacrificial electron donors and pH values tested $[Cu/TiO_2]$=0.2 $g{\cdot}L^{-1}$. The accumulated solar energy ($kJ{\cdot}L^{-1}$) associated to each energy production appears attached to each column.

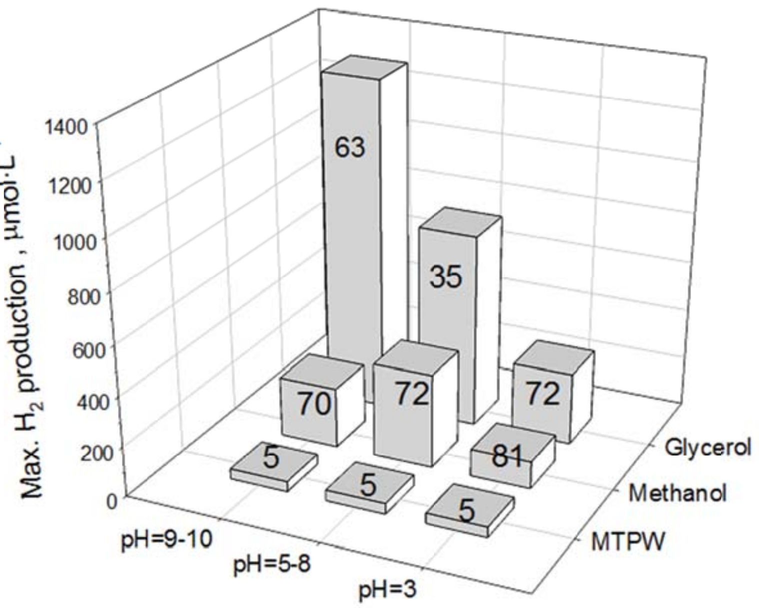


Figure 99. Best H_2 productions for the different sacrificial electron donors and pH values tested [Cu/TiO_2]=0.2 g·L^{-1}. The accumulated solar energy (kJ·L^{-1}) associated to each energy production appears attached to each column.

TRICERATOPS. Efficient technologies for removal of contaminants of emerging concern, listed in 2013/39/EC Directive or significant risk substances according to 2008/105/EC Directive

Participants: CIEMAT-PSA, UPV (Escuela politécnica Superior de Alcoy), Instituto Catalán de la Investigación de Agua (ICRA)

Contacts: Dr. S. Malato Rodriguez; sixto.malato@psa.es

Funding agency: Spanish Ministry of Economy and Competitiveness (Reference CTQ2015-69832-C4-1-R)

Background: The initial hypothesis focuses different advanced oxidation processes, operational procedures and different ways of combining them for wastewater treatment. The project will focus water containing microcontaminants (MCs) of important concern identified by EU or already identified as risk substances for water.

Objectives: (ii) Elimination by novel technologies of priority or emerging concern MCs present in wastewaters and listed in EU legislation; (ii) Propose photoreductive electron transfer processes for the elimination of contaminants recalcitrant to oxidation; (iii) Waste and wastewater valorization for elimination of MCs; (iv) Design of new photoreactors based on solar irradiation and LEDs; (v) Integration of nanofiltration procesess and novel AOPs.

Results in 2017: CIEMAT-PSA tasks in this project have been a continuation and complementary to the work done in 2016. Selected MCs (Terbutryn, chlorfenvinphos, pentachlorophenol and diclofenac) have been treated by photo-Fenton process at neutral pH using poliphenols from cork boiling wastewater (CBW) as Fe-complexing agents and studying the stability of iron using olive mill wastewater. It has been applied an Omics approach (metabolomics approach to analysis of LC-HRMS data acquired before and after CBW treatment) to the detection of persistent transformation products during CBW treatment. Microbiological techniques based on the combination of simple optical microscopy observation, culture-based studies with qPCR and microbial genomics (applying metagenomics) have been carried out in order to study the adaptation process followed by microbial population from conventional WWTP activated sludge when the system is fed with CBW. The new ozonation reactor connected to a 70-mm CPC photoreactor has been used for the treatment of Terbutryn, chlorfenvinphos, pentachlorophenol and diclofenac. Start-up of photo-electro-Fenton pilot plant (see figure 98). See also: http://www.psa.es/es/projects/triceratops/index.php

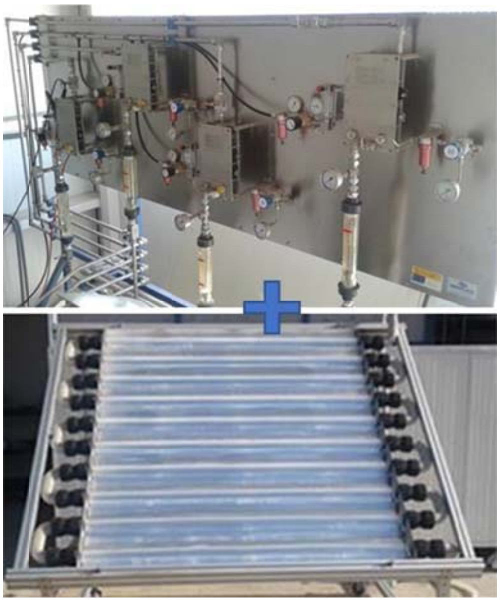


Figure 100. Photo-electro-Fenton pilot plant (4 electro cells combined with a solar CPC) for testing in TRICERATOPS project.

ALICE. Accelerate Innovation in Urban Wastewater Management for Climate Change

Participants: University of Ulster, Nothern Ireland Water Litd., The Queen´s University of Belfast, Dublin City University, Dioenergy Ltd., Asociación BC3 Basque Centre for Climate Change, CIEMAT-PSA, GDW ESAMUR, Universita Degli Studi di Macerata, REINN Srl., Aset spa., University of Cyprus, Militos Symvouleutiki A.E.

Contacts: Dra. Isabel Oller; isabel.oller@psa.es

Funding agency: H2020- Marie Skłodowska-Curie Action (RISE) (GA 734560)

Background: The coming decades are likely to see some geographical areas experiencing a higher risk of flooding and other areas exposed to higher risks of droughts. More green and grey infrastructures, implementing increased effluent treatment including cooling and a greater recycling and reuse will pose a challenge in terms of financial sustainability of wastewater facilities.

Objectives: Accelerate innovation in urban wastewater management to address the future challenges arising from climate change. The project will identify solutions and seek to remove barriers for their implementation. The aim will be achieved through secondments and the transfer of knowledge, creating an effective interdisciplinary and inter-sectoral cooperation among the partners involved.

Results in 2017: CIEMAT-PSA completed the first secondment scheduled in the Annex I of the ALICE MCSA from the 4th of September to the 6th of December 2017 in Northern Ireland Water Company and in the University of Ulster (in the Nanotechnology and Integrated Bioengineering Centre). The secondment was carried out by an ESR in the topic of photo-electro-chemical and solar water disinfection. The efficiency of a lab scale photo-electro-chemical reactor with TiO_2 electrodes by using a UV-B lamp was evaluated for the elimination of antibiotics resistant bacteria such as E.Coli, Salmonella and E. faecalis. In addition, CIEMAT-PSA as the leader of WP 4 related to reclaimed wastewater reuse and resource recovery, reported the results obtained through 2017. It must be highlighted the development of advanced analytical tools for monitoring selected emerging contaminants (carbamazepine, flumequine and thiabendazole) and possible metabolites transfer into crops after irrigation. Pathogens selected were antibiotic resistant E. coli and E. faecalis strains. In addition, the capability of different solar processes for UWW disinfection has been conducted at PSA (figure 99). This study was conducted using freshly collected UWW from the secondary effluent of the UWWTP of El Bobar (Almeria, Spain). See also: https://www.alice-wastewater-project.eu/

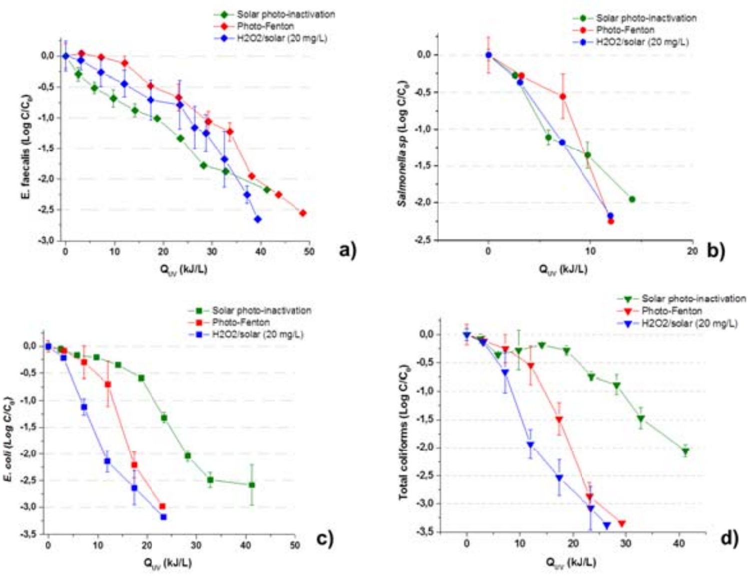


Figure 101. UWW disinfection by solar photocatalytic (photo-Fenton) and photochemical (solar photo-inactivation and H_2O_2/solar) processes under natural sunlight within CPC reactor: a)*E. faecalis* b) *Salmonella sp* c) *E. coli* and d) Total coliforms inactivation profiles against cumulative solar UV dose delivered by unit of time and volume of water treated (Q_{UV}).

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

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-PSA, Panepistimio Ioanninon, Universidad Politecnica de Valencia.

Contacts: Dra. Isabel Oller; isabel.oller@psa.es

Funding agency: 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.

Results in 2017: AQUALITY training network started in October 2017 so only few activities were carried out. The kick of meeting took place in Turin the 25th of October 2017. In addition, the first Workshop on PhD supervision took place also in Turin the 23rd and 24th of October 2017 held by Dr. Pia Bogelund form the University of Alalborg, UNESCO Centre for Problem Based Learning in Engineering Science and Sustainability. The recruitment process for the two ESRs that should be incorporated at the Solar Treatment of Water Unit at PSA started on November 2017 and was published in EURAXESS website. For more details visit the website: https://www.aquality-etn.eu/

5.4 UNIT STAFF PHOTO

6. HORIZONTAL R&D ACTIVITIES

6.1 STAGE-STE

Work Package 8: Materials for Solar Receivers and STE Components

Participants: CIEMAT, DLR, CNRS, FISE, ENEA, CEA, LNEG, CNR, CENER, TECN, CRAN, TKN, IST-ID, SENER, HITIT, SCHOTT, ASE, ASNT, COBRA.

Contacts: Gema San Vicente (gema.sanvicente@ciemat.es, Task 8.2.4); Aránzazu Fernández García (arantxa.fernandez@psa.es, Tasks 8.1 and 8.3); Antonio Avila (Antonio.avila@ciemat.es, Task 8.2.6)

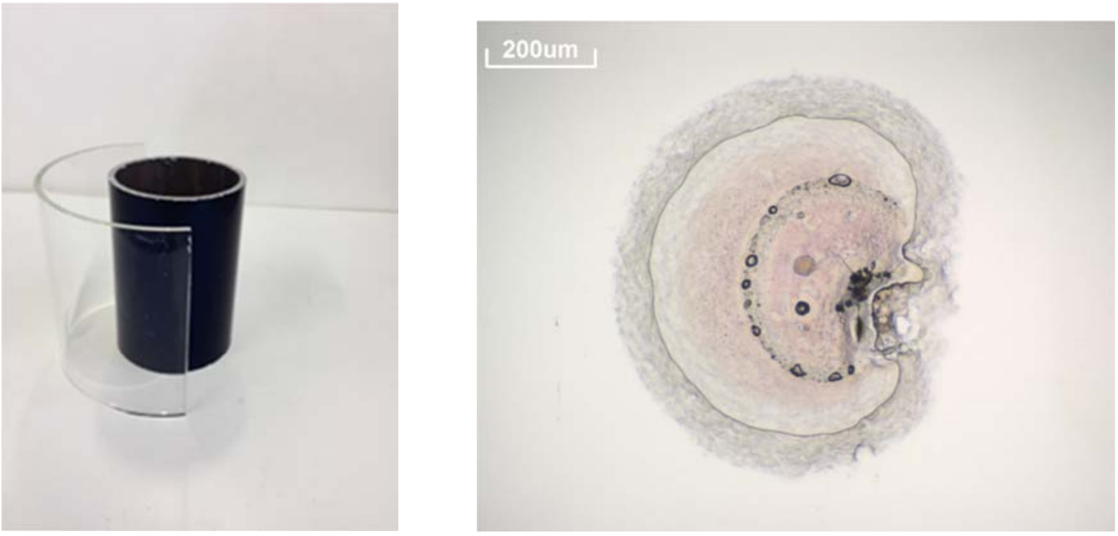
Funding agency: EU-7FP-ENERGY-2013.

Background: Research has been conducted towards developing a durability testing guideline for solar reflectors to predict material failure in advance. By and large, the study of new solar receiver designs is a required investigation due to the need to improve their thermal performance at high temperatures. In addition, it has appeared several methods for the measurement of parameters in linear receivers and it is necessary to validate them.

Objectives: CIEMAT's participation is focused on: i) developing methods of accelerated ageing for reflectors that provide estimations of degradation over lifetime; ii) comparing the procedures used to perform optical measurements of absorptance, emittance and transmittance on tubular samples of line focusing receivers; iii) analysing the suitability of enhanced materials for high temperature applications; iv) investigating the occurrence of abrasion under desert conditions and simulate it under laboratory conditions.

Results in 2017: Concerning the topic related to the development of a guideline for durability testing of typical silvered-glass solar reflectors (Task 8.1), a round robin test to compare the accelerated aging tests according to the new UNE standard among the participating partners (CEA, CENER, CIEMAT/DLR, LNEG and TECNALIA) was totally accomplished. According to the results obtained, the average standard deviation among the five laboratories regarding the hemispherical and specular reflectance losses is in the order of 0.2% and 0.3%, respectively. The average standard deviation of the maximum non-protected edge corrosion penetration, the number of corrosion spots per dm² (>200µm) and the number of bubbles per dm² in the paint layer was 0.19 cm, 5 corrosion spots and 11 bubbles, respectively. These deviation values are in the same order of the average value, and therefore the methodology used should be improved. Also, several reflectors that have been exposed outdoors in commercial plants were analysed by CIEMAT/DLR to identify the reflectance decay and the degradation mechanisms appearing during operation.

Regarding to task 8.2.4, a Round Robin Test which compares the procedures used to perform optical measurements of absorptance, emittance and transmittance on tubular samples of line focusing receivers has been performed. The participating laboratories were CENER, DLR, CIEMAT, LNEG and CEA. The results have shown that the equipment and procedures used by the 5 labs to obtain the optical measurements performed in solar wavelength range (solar transmittance and solar absorptance) in curve samples, gave place to comparable results. Differences in values equal or lower than 1% were obtained. However, no comparable results were obtained by the labs in thermal emittance values. 2 labs obtained similar values but they are almost twice the value obtained for other lab. Even using the same equipment to obtain the measurements, no comparable results were obtained. This fact revealed that it is necessary to study deeply the testing procedures used by the laboratories in order to obtain comparable data.



(a) (b)

Fig. 102. Samples tested in Round Robin Test of optical measurements (Task 8.2.4.2) (a) and example of corrosion spot localized during the round robin test of solar reflectors (Task 8.1) (b).

In WP 8.2.6, the main objective is the design and testing of a high-temperature solar absorber using a low-cost material and a simple manufacturing process. For that purpose, an absorber consisting of alumina pebbles with improved absorptance was designed. During the last year of the project, four optimal configurations were thermally evaluated. Each configuration was tested in three different optical conditions: 1) without coating, 2) Coated with commercial Pyromark 2500 and, 3) Coated with CIEMAT-PSA developed based on spinel with alumina particles.

Fig. 99 shows the thermal comparison of the different configurations tested with different optical conditions; moreover, Fig. 100 presents the hemispherical reflectance of the pebbles before and after the tests.

It is concluded that the different configurations of alumina pebbles are not able to achieve the required efficiencies for power tower technology, even at lab scale. However, it is noteworthy the influence of the spinel based coating in the performance of the different configurations, with better results than Pyromark coating at almost all the conditions.

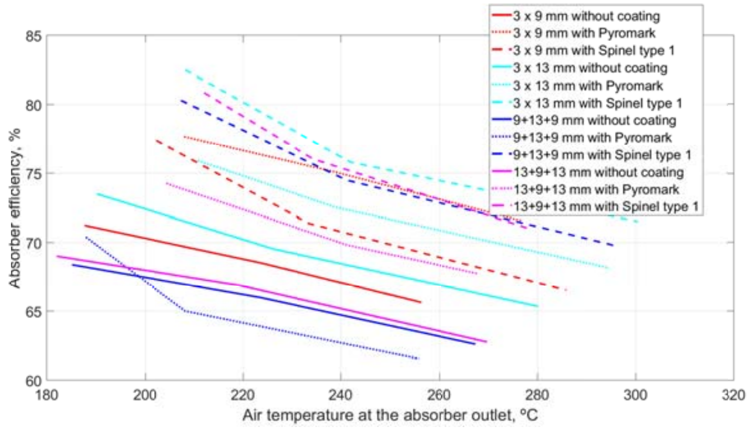


Fig. 103. Comparison of the 4 different configurations without coating and with two different coatings

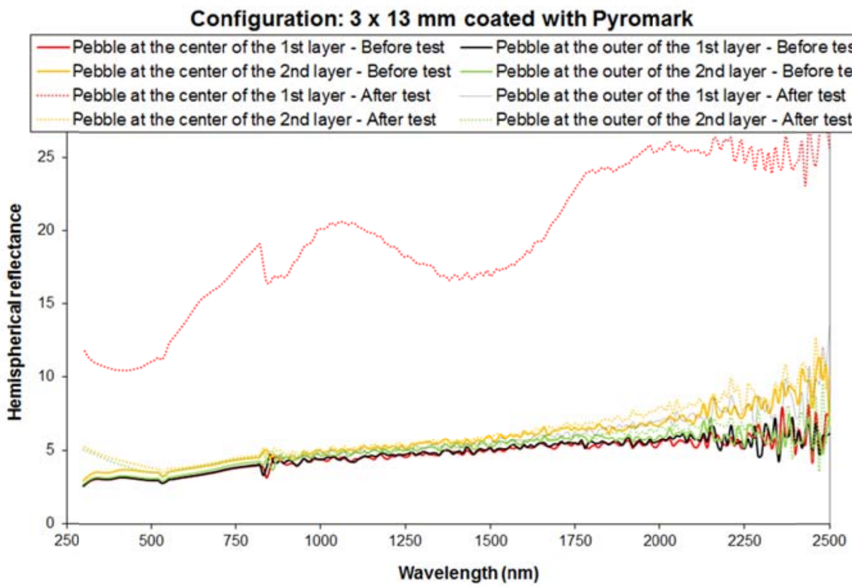


Fig. 104. Comparison of the hemispherical reflectance of the pebbles coated with Pyromark 2500 located at different positions before and after the tests for the configuration 3x13mm

With respect to the study of the erosion of reflectors under desert conditions (8.3), a guideline with the adequate methodology to conduct accelerated aging tests was developed.

Work Package 11: Line-focusing STE Technologies

Participants: CIEMAT (WP11 coordinator), CNRS, Fraunhofer-ISE, ENEA, CEA, LNEG, CENER, Tecnalia, University of Evora, Cranfield University, Tekniker, SENER, SUNCNIM, Acciona Energía, Archimede Solar Energy, Abengoa, COBRA.

Contacts: Loreto Valenzuela (loreto.valenzuela@psa.es)

Funding agency: EU-7FP-ENERGY-2013 (G.A. no: 609837).

Background: A big deployment of large commercial solar fields for electricity generation, specially using parabolic troughs has appeared in the last 10 ten years. In addition, it has been identified by different stakeholders the big potential for the application of line-focusing solar collectors' technology for distributed power and process heat generation, and solar heating and cooling applications.

Objectives: CIEMAT's participation is focused on: i) explore and develop new concepts of medium temperature line-focusing collectors; ii) work in the modelling and simulation of parabolic troughs fields using water-steam as heat transfer fluids; iii) define and validate dynamic solar field testing procedures; iv) define and analyse new methodologies for on-site characterization of line-focus collectors and their components in large commercial solar fields.

Achievements in 2017: In the context of Task 11.1.1 CIEMAT, in collaboration with Tecnalia, Cener and University of Evora, completed the preparation of the medium temperature solar collector's database that is available at the following link http://www.stage-ste.eu/keydocuments/solarthermalcollectors.php (see Fig. 103). At the time of preparing this summary, the database includes information of 74 collectors available in the market. It is planned to maintain it during the coming years in the framework of new projects and common activities between the partners involved in its preparation.

In the context of Task 11.2, CIEMAT has coordinated the working groups of thermal inspection of receivers, inspection of reflectance/soiling of reflectors, and inspection of other components (structures, tracking mechanisms, etc.) in large solar fields (Task 11.2.2). In addition CIEMAT has participated in task 11.2.1 to evaluate the performance of collectors installed in solar power plants. Main activities completed this last year of project are:

- Evaluation of solar field data from parabolic trough power plants owned by ACCIONA and SENER. Thermal performance of collector loops and sectors of the solar fields have been analysed following an steady-state method applied by CIEMAT in other qualifications and the quasi-dynamic testing methodology proposed in ISO 9806:2017, recently updated.
- CIEMAT completed an outdoor test campaign at the HTF test loop to quantify vacuum status level of solar receiver tubes for PTCs by mean of infrared thermography.
- CIEMAT also has participated in the inter-comparison of portable reflectometers in solar power plants owned by ACCIONA and SENER. During this last year of project there have been evaluated data measured in ACCIONA and SENER power plants in 2016. Differences found in the measurements of specular reflectance taken with three instruments used during the test campaigns (15R by Devices&Services, Condor by Abengoa, and PFlex by Fraunhofer-ISE) are mainly explained by their different acceptance angles.

Fig. 105. (Left) Web interface of the medium temperature solar collector's database developed in the framework of the STAGE-STE project, and (right) example of datasheet of a particular collector generated by the web tool.

6.2 SFERA II

SOLAR FACILITIES FOR THE EUROPEAN RESEARCH AREA: SECOND PHASE

Participants: *CIEMAT (coordinator), DLR, CNRS, PSI, ETHZ, ENEA, CEA, INESC-ID, UNIVERSITY OF EVORA, UNILIM, ESTELA and UTV.*

Contacts: Isabel Oller Alberola (Technical Coordinator) (isabel.oller@psa.es), Ricardo Sánchez (Project manager and Transnational Access Coordinator) (ricardo.sanchez@psa.es).

Funding agency: European Commission, *FP7-INFRA-2012-1.1.1.*

Background: CSP Research Infrastructures in Europe have served through the last 30 years as research tools to demonstrate the concept feasibility by exploring different pathways on how to produce high temperature heat, electricity and, solar fuel using concentrating solar radiation. Nowadays, the key point is to cooperate with the industry in order to gain a significant market share.

Objectives: The purpose of this project is to integrate, coordinate and further focus scientific collaboration among the leading European research institutions in solar concentrating systems that are the partners of this project and offer European research and industry access to the best-qualified research and test infrastructures.

Results in 2017: SFERA-II project is divided into three main activities: Networking, Transnational Access and Join Research Activities.

Regarding Networking activities, the fourth training course was prepared and conducted by DLR researchers at PSA (CIEMAT) in April 2017. The course covered optical and thermal components testing of parabolic troughs and the influence on the system efficiency. The selection of attendants ended in February 2017 with the selection of fifteen industry engineers and researchers from four countries: Spain, Germany, Turkey and Morocco. It is particularly worth mentioning the high interest of engineers working in operation and maintenance of operative solar power plants in this last SFERA II training course. In addition the organization of the 4th SFERA-II Doctoral Colloquium (15 17 May 2017) was carried out by DLR to improve sharing between the PhD students of the different partners' institutions. There were 35 PhD students registered from all partners of the project. The 4th SFERA-II school was linked to the Doctoral Colloquium (DLR – 18-19 May 2017) dedicated to Modelling and Validation.

The Final SFERA-II Coordination Meeting and Steering Committee was held at CIEMAT-PSA the 14th and 15th of November 2017. See picture below (figure 104).

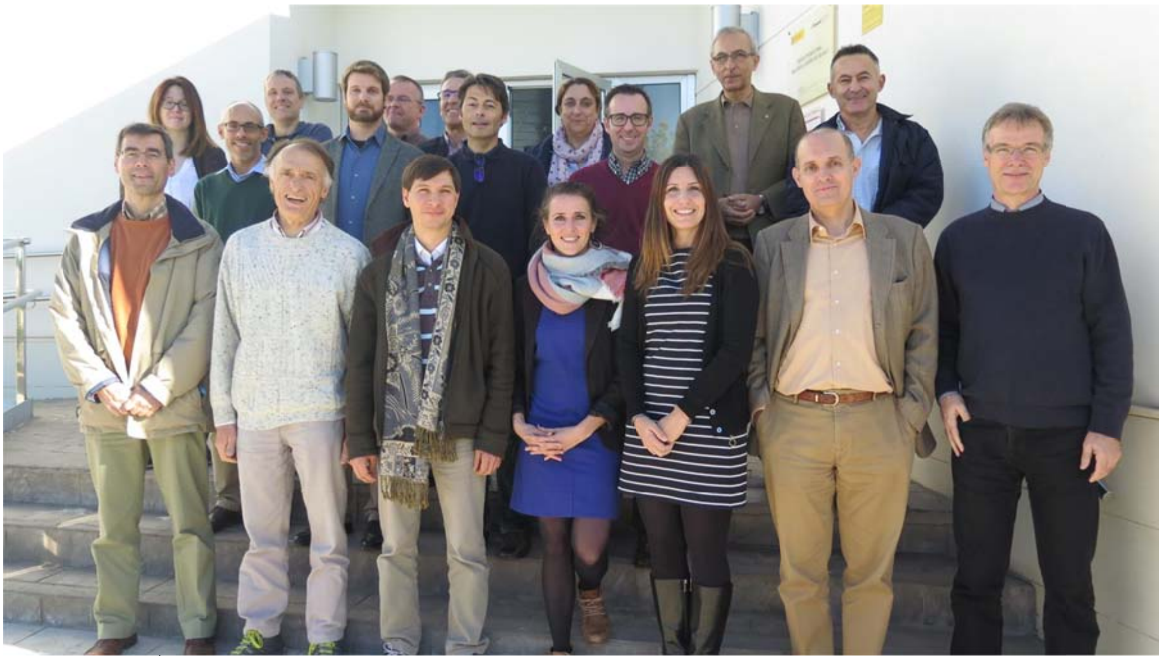


Figure 106. 3rd SFERA Doctoral Colloquium organized by PSA-CIEMAT in Hotel Rodalquilar (Almeria, Spain) (6-8 of June 2016).

6.3 NESTER

NETWORK FOR EXCELLENCE IN SOLAR THERMAL ENERGY RESEARCH

Participants: CYI (Cyprus, Coordinator), CIEMAT-PSA (Spain), ENEA-UTRINN (Italy), CNRS-PROMES (France), RWTH-AACHEN (Germany).

Contacts: Julian Blanco, julian.blanco@psa.es
Diego Alarcón, diego.alarcon@psa.es

Funding agency: European Commission, H2020-TWINN-2015

Background: The NESTER network comprises of four leading institutions (CIEMAT, ENEA, CNRS-PROMES and RWTH – Aachen) with a comprehensive know-how in the field of solar energy research and operating some of the most important facilities worldwide. This networks target is to enhance CYI capabilities and, as a consequence, to positively impact on developing the knowledge economy of Cyprus. The substantial investments made/planned by CYI in infrastructure and personnel will thus become more efficient and competitive allowing claim to international excellence.

Objectives: The NESTER project aims in upgrading the scientific and innovation performance of the Cyprus Institute (CYI) in the field of Solar-Thermal Energy (STE). The upgrade will be achieved by embedding the Institute's activities in a network of excellence, which will provide access to the latest know-how and facilities, train CYI's scientific and technical personnel and link it with the European Industry. A number of activities are proposed in a detailed program which includes training and know-how transfer, seminars and networking events with European, Eastern Mediterranean and Middle East partners, autumn school activities, public outreach and awareness and networking events.

Achievements in 2017: Main contribution of CIEMAT to this project during 2017 was in the topic of Thermal Energy Storage. Since in 2017 the second week of the 2nd Annual Autumn School on Concentrated Solar Technologies (CST) was focused on Storage, the PSA Thermal Storage unit actively participated giving around 50% of the lectures that week, sharing its experience on thermocline modelling to look for the potential synergies on modelling issue with CYI. Also, the Solar Concentrating Systems unit collaborated with a visit of one engineer to CYI to, firstly, perform a complete training about the correct use of portable reflectometers, including practical lessons using a 15R-USB model); secondly, three test campaigns were performed for optically characterize the performance of the small heliostat field of the PROTEAS facility, the linear Fresnel system installed on the KEPA school, and two demo CYI heliostat units. All these actions were designed to ensure the sustainability of CYI, as well as the continuation of cooperation activities, well beyond NESTER project finalization.

6.4 INSHIP

INTEGRATING NATIONAL RESEARCH AGENDAS ON SOLAR HEAT FOR INDUSTRIAL PROCESSES

Participants: FRAUNHOFER (Germany), AEE-INTEC (Austria), CIEMAT (Spain), DLR (Germany), CNRS (France), ENEA (Italy), ETHZ (Switzerland), CEA (France), CYI (Cyprus), LNEG (Portugal), CTAER (Spain), CNR (Italy), CENER (Spain), TECNALIA (Spain), UEVORA (Portugal), IMDEA (Spain), CRANFIELD (UK), IK4-TEKNIKER (Spain), UNIPA (Italy), IST-ID (Portugal), FBK (Italy), CRES (Greece), METU (Turkey), EERA AISBL (Belgium), UNINA (Italy), UNIFI (Italy), US (Spain), CIC Energigune (Spain).

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Diego Martínez, diego.martinez@psa.es

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

Background: Process heat is recognized as the application with highest potential among solar heating and cooling applications. Solar Heat for Industrial Processes (SHIP) still presents a modest share of about 0.3% of total installed solar thermal capacity. As of today's technology development stage is quite restricted to low temperature applications, so INSHIP is focusing on CSP/STE technologies to widen the scope of industrial applications to a temperature range between 80 – 1500 °C. INSHIP project correspond to a new funding scheme (European Common Research and Innovation Agenda-ECRIA) designed by the European Commission as the next step beyond the current Integrated Research Agendas (IRP) and specifically targeting EERA JPs.

Objectives: INSHIP is a framework engaging major European research institutes with recognized activities on SHIP, into an integrated to achieve the coordination objectives of: more effective and intense cooperation between EU research institutions; alignment of different SHIP related national research and funding programs, avoiding overlaps and duplications and identifying gaps; acceleration of knowledge transfer to the European industry, while developing coordinated R&D TRLs 2-5 activities with the ambition of progressing SHIP beyond the state-of-the-art.

Results in 2017: In addition to the PSA-CIEMAT contribution to a large number of technical activities (WPs 2 to 5), main role in this project is the coordination of WP6 (Integrated SHIP research infrastructures) and WP8 (Advanced Networking Activities). In the context of WP6, the mapping of RTD SHIP infrastructures & resources was initiated to check if the current existing facilities fulfil all present and future needs of the scientific community and industrial sector. Also, mobility scheme addressing staff personnel, as well as the program to access to Research Infrastructures, were defined and started. In the context of WP8, the first questionnaire dealing with the "Analysis of needed national and regional innovation strategies on SHIP", was prepared being ready for its distribution.

6.5 WASCOP

WATER SAVING FOR SOLAR CONCENTRATING POWER

Participants: CEA, DLR, CIEMAT-PSA, Cranfield University, Fundación Tekniker, MASEN, Rioglass Solar, Archimede Solar Energy, OMT Solutions, Hamon D´Hondt, AMIRES.

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

Funding agency: EU-H2020-LCE-02-2015.

Background: CSP plants use significant amounts of water to function properly. Water is a restricted resource in the parts of the world where the majority of CSP plants are installed. Water saving is therefore one of the major issues to ensure a financially competitive position of CSP plants and their sustainable implementation.

Objectives: To develop a revolutionary innovation in water management of CSP plants, a flexible integrated solution (or toolbox) comprising different innovative technologies and optimized strategies for the cooling of the power block and the cleaning of the solar field, with the aim of a significant reduction in water consumption (up to 90%).

Achievements in 2017: CIEMAT-PSA is involved in this project through its Solar Concentrating Technologies and Desalination Units. During the second year of the project, the application of anti-soiling coatings on reflectors and absorber tubes has been evaluated to decrease water consumption in cleaning. Samples of both components were submitted to a deep accelerated aging test campaign to select the most appropriate coating among different options in the case of the absorber tubes and to check the durability of the already selected coating in the case of the reflectors. Also, the testing facilities to assess several cleaning tools (dust barriers, anti-soiling coating for reflectors and absorber tubes, low-cost soiling sensor and ultrasonic cleaning system) under real outdoor conditions have been prepared and installed (see Figure 105). In some cases, the experiments were already started at the end of 2017. We have also defined the piping and instrumentation diagram and the implantation of the test loop of the new hybridized cooler prototype to be installed at PSA facilities (see figure 106). The test campaign to be performed, control loops, signals, electrical connections, etc. have also defined. After that, the procurement process has been carried out for the acquisition of all the components of this test loop. Pressure transmitters, flow meters, pumps, valves and a steam generator (see figure 107) have been already acquired. In addition, simplified models for a latent storage system to be used as either indirect or direct cooling systems have been developed. The evaluation of a direct hybrid cooling system composed of a latent storage and an air-cooled condenser in a 50MW$_e$ parabolic-trough power plant has been performed. In terms of finding which materials may be the best one for this application, some commercial products have been fully characterized (melting temperature and enthalpy and heat capacity figures have been obtained) and their behaviour under daily melting/freezing cycles have been obtained.

Figure 107. Picture of the test bench for the anti-soiling coating for reflectors (left) and absorber tubes (right)

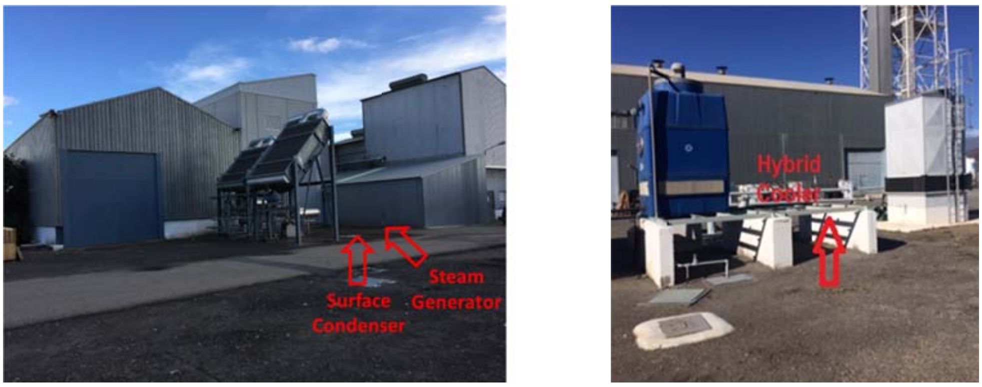


Figure 108: Picture of the implantation of the new equipment to be installed at PSA facilities

Figure 109. Steam generator already purchased at PSA facilities

7.TRAINING AND EDUCATIONAL ACTIVITIES

The ruling principle of the Plataforma Solar de Almería 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 forty-five students of different nationalities are admitted each year so that we can transmit the knowledge of solar thermal technology accumulated at the PSA in its more than 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 an agreement with the University of Almeria (UAL) and with the own program for young researchers of CIEMAT.
- European funded 'Erasmus' grants, for students from other countries, mainly German.
- Management of miscellaneous specific educational cooperation agreements with other entities that send students to the PSA (Universities of Cádiz, Almería, País Vasco, Dalarna-Sweden, Politecnico di Torino-Italy, Blida-Algeria, CDER-Algeria, UIR- Morocco, Antofagasta-Chile, Santiago de Chile-Chile, AUCC-Chile, Veracruzana-Mexico, Royal College of Surgeons-Ireland, Hamburg University of Technology, Salesiana-Ecuador, Concepción-Chile, ICO-Mexico, Palermo-Italy etc.)

The close and enduring collaboration between CIEMAT and University of Almería has allowed carrying out the first edition of the Official Master's in Solar Energy. The hallmarks of this course, along with its quality, make it an attractive proposition for students, both Spanish and those from other countries, who want to gain a first-rate qualification in the field of solar energy and its many applications.

Related with the Educational Cooperation Agreement between CIEMAT-PSA and the University of DALARNA (Sweden), from 16th to 24th October, 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 European Solar Engineering School, ESES (University of Dalarna).

The PSA is a founding member of the 'Alliance of European Laboratories on Solar Thermal Concentrating Systems' (SolLab). This virtual laboratory is made up of the main European concentrating solar energy research institutes, that is, PROMES-CNRS in Odeillo (France), the DLR Solar Energy Division in Cologne (Germany), the Renewable Energies Laboratory of the Federal Institute of Technology in Zurich (ETHZ, Switzerland), the Paul Scherrer Institute in Zurich (PSI, Switzerland) and the CIEMAT itself.

Founding in 2004 of SolLab opened new possibilities for scientific development of researchers training at the PSA. One of the joint SolLab activities is an annual seminar for Ph.D. students from the five different institutions (Doctoral Colloquium), which is part of the activities of the European project so-called SFERA-II (Solar Facilities for the European Research Area. Second Phase) at the same time.

The 13th SOLLAB was organized by the DLR Solar Energy Division and took place in Berlin, Germany. The Colloquium was held between the 15th and the 17th May 2017. Afterwards, the SFERA Summer School was hosted at the same location from the 18th to the 19th May 2017. It was focused on Modelling and Validation.

8. EVENTS

07/02/2017
Technical visit
Mr. S. Malik, director manager of Megawatt Solutions Co. from India, visited the PSA research facilities receiving information about current activities in solar thermal technologies for potential applications in regional development.

08/02/2017
Technical visit
A group of 20 students of the Postgraduate ClimaDesign Master Course, from Technical University of Munich, Germany, visited PSA as part of the training activities on Energy Efficiency in Buildings.

20/02/2017

Technical visit

Prof. Marcelo Serrano, public official from the Ministry of Energy of Chile in training stage at Ciemat, visited the PSA installations to know about CSP technologies in relation with the development and implementation of RE.

02/03/2017

Workshop

E. Zarza participated in the Workshop "*Oportunidades de la Energía Solar Termoeléctrica*" organized by PROTERMOSLLAR and CIEMAT at the international event GENERA-2017 held at Madrid to present the main R+D lines selected by the STE sector to speed up cost reduction.

07-08/03/2017

Institutional Meeting

The PSA hosted the visit of the Delegation from Lebanon in the frame of the TAIEX Study Visit on Small Concentrated Solar Power Plants, with the aim of improve the experience of specialists on renewable energy technologies and applications.

13/03/2017

Technical Visit and Meeting

Visit to PSA of researchers of the Engineering School of Seville to check potential R+D collaboration with PSA.

17/03/2017

Lecture

Invited lecture on "***Thermal Energy Storage Introduction*"** of Esther Rojas at ENEA´s premises in Rome, Italy.

21/03/2017

Technical Visit and Meeting

Visit to PSA of TEWER Ingeniería with representatives from Brazilian companies (CSEP, EUDORA Energia, RTB Holding Energia, P&D Aneel and Institutos Lactec) to know our experimental facilities.

21/03/2017

Technical visit

A group of engineers and officers from TEWER Co. visited PSA as part of the training activities in Spain related to solar thermal power plants.

4-6/04/2016

Official Meeting

Participation of E. Zarza in the 92nd meeting of the Executive Committee of SolarPACES held at Thessaloniki, Greece.

5-7/04/2016

Official Meeting

Participation of Rocio Bayón in the ***Kick-off meeting of the IEA SHC/ECES Task 58-33. Material and Component Development for Thermal Energy Storage***, held at Lyon, France.

11-12/04/2017

Lecture

G. Zaragoza was invited to participate in a workshop on costs of desalination organized by MEDRC (Muscat, Oman).

18/04/2017

Lecture

Invited lecture on "***Centrales Termosolares: peculiaridades, ventajas socio-económicas, potencial comercial y posibles mejoras tecnológicas***" of Eduardo Zarza at the Engineering School of Málaga

20/04/2017

Lecture

Invited lecture of Sixto Malato at "Workshop & NIS colloquium". Keywords: environment, water, sustainable materials, circular economy. Towards 2018-20 European proposals", held at Università di Torino – Dipartimento di Chimica (Italy).

24-26/04/2017

Lecture

Invited lecture of Leonidas Pérez on "Water Contaminants Annual Forum (AFWC) and SCIEX User Group Meeting", held on Freising (Germany).

26/04/2017

Technical Visit and Meeting

Visit to PSA of D. Gabriel Barthelemy, (Promotion and Cooperation Department of CDTI) to know the PSA facilities and to explain the funding possibilities for R+D activities available at Spanish CDTI.

5/05/2017

Technical Visit and Meeting

Visit to PSA of Spanish STE plant operators from Elecnor to know the PSA facilities and the R+D activities developed at PSA.

10/05/2017

Official meeting

G. Zaragoza participated in the meeting of the Board of Directors of the European Desalination Society in Tel-Aviv (Israel).

11/05/2017

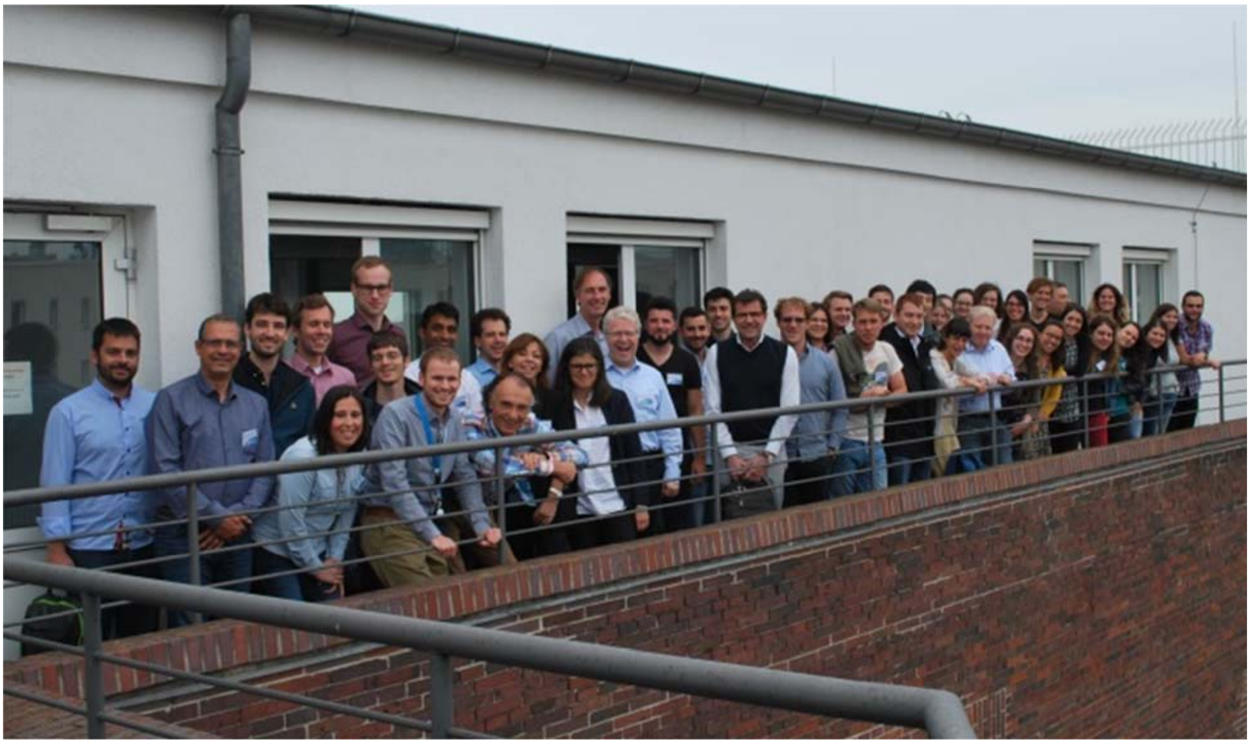
Official meeting

A Delegation from DLR, headed by their General Director Mrs. Pascale Ehrenfreund and hosted by the Deputy GD of Ciemat, Mrs. Mª Luisa Castaño, visited PSA facilities in the frame of the bilateral cooperation agreement.

15-17/05/2017

Educational activity

Participation of A. Segura, M.E. Carra and L. Valenzuela in the SOLLAB Doctoral Colloquium held at Berlin (Germany on May 15-17, 2017



Participants in the SolLAB 2017 held in Berlin (Germany)

29/05/2017

Technical visit

The PSA hosted the visit of a group of Cuban specialists in the frame of the cooperation under the Hybridus Project, financed by the AECID and with Ciemat participation, with the aim of improve the training on renewable energy technologies and applications.

5/06/2017

<u>Technical Visit and Meeting</u>

Visit to PSA of researchers from the Chilean university Adolfo Ibañez to know our experimental facilities and check potential collaborations to use concentrating solar energy in the mining sector of Chile.

12/06/2017

<u>Workshop</u>

E. Zarza participated in the international Workshop on "***Materials resistant to extreme conditions for future Energy systems***" organized by the European Commission in collaboration with the Science Academy of Kyiv and held in Kyiv, Ukraine. He explained the *Technical Requirments for Concentrating Solar Thermal Systems Materials*.

14/06/2017

<u>Official meeting</u>

G. Zaragoza organized and chaired a meeting of the Working Group Renewable Energy and Desalination of the European Water Platform WssTP in Brussels (Belgium).

15/06/2017

<u>Technical visit</u>

A group of representatives from regional authorities and private institutions of Coquimbo (Chile), invited by EXTENDA, visited PSA interested on research and technological development activities related to solar thermal power plants.

28/06/2017

<u>Technical visit</u>

Japanese researchers and engineers from TOYOTA Corporation, the Tokyo Institute of Technology, Chiyoda Cooperation and the Japan Fine Ceramics Center visited the PSA installations to discuss specific research topics related to development and evaluation of components for parabolic-trough collectors working with high temperature working fluids.

Visit of Totoya company (Japan) to PSA test facilities.

04/07/2017

Doctoral Thesis

Alba Ruiz defended the Doctoral Thesis “Evaluación de sistemas comerciales en espiral de destilación por membranas y su aplicación al tratamiento de agua”. UAL.

4/07/2017

Lecture

Invited lecture on “**"La Plataforma Solar de Almería: más de 35 años de investigación en la provincia de Almería"** of Eduardo Zarza at the Summer School of the University of Almería held at Roquetas de Mar (Almería, Spain).

05/07/2017

Lecture

Invited lecture of Sixto Malato on a Summer School of the University of Almería titled: “Energías renovables: claves para un nuevo impulso en la provincia de Almería”, held in Roquetas de Mar, Almería (Spain).

06/07/2016

Doctoral Thesis

Maria Castro Alférez defended the Doctoral Thesis “Kinetic modelling of the *Escherichia coli* inactivation in water by solar radiation: applications to SODIS”. University of Almería (Spain).

10/07/2017

Lecture

Invited lecture of Sixto Malato on “2nd Summer School on Environmental Applications of Advanced Oxidation Processes and Training School on Advanced Treatment Technologies and Contaminants of Emerging Concern” (Treatment of CECs by solar driven AOPs), held at Biblioteca Municipal Almeida Garrett, Porto (Portugal).

26/07/2017

Technical visit

Professors from Tecnológico de Monterrey (México) visited the PSA to know the experimental facilities and discuss about the educational agreement between this institution and CIEMAT signed in 2017. First PhD student from México will stay at PSA to collaborate in topics related to parabolic-trough technology.

Visit of Tecnológico de Monterrey (México) to PSA test facilities.

04/08/2017

Workshop

E. Zarza and L. Valenzuela participated in the Workshop “***Energy Efficiency and Industrial Solar Thermal Application***” organized by the Turkish company Lucida Solar at the Teknopark of Izmir (Turkey) to explain the potential of the Industrial Process Heat applications and the basic principles of line-focus concentrating technologies.

01/09/2017

Doctoral Thesis

Juan José Serrano defended the Doctoral Thesis “Thermal-hydraulic and optical modeling of solar Direct Steam Generation systems based on Parabolic-Trough Collectors”. U. de Málaga.

06/09/2017

Lecture

Invited lecture on “***Integrating Thermocline Storage Systems in STE plants***" of Esther Rojas at University of Evora, Portugal

18/09/2017

Official Meeting

Participation of Isabel Oller as leader of one subtak in the first official meeting for the definition of the new task of the International Energy Agency, Solar Heating and Cooling, related to “Solar Energy in Industrial Water and Wastewater Management”, held in AEE-INTEC in Graz (Austria).

26-29/09/2017

International Congress

CIEMAT-PSA participated in SolarPACES Conference once again, presenting 16 oral presentations and 13 posters.

CIEMAT´s researchers at SolarPACES 2017

29/09/2017

Technical visit

A group of 40 students of BioTecnoEncuentro in Almería visited the PSA installations as part of the training activities interested on research and technological development related to solar thermal power plants.

01/10/2017

Official Meeting

Participation of E. Zarza in the *93rd meeting of the Executive Committee of SolarPACES* held at Calama, Chile.

4-6/10/2017

Dissemination and divulgation

J. Fernández and E. Zarza participated in the ***Workshop sobre Energía Solar Térmica de Concentración,*** organized by the CYTED tematic Network ESTCI in Ciudad de La Plata (Argentina)

One of the sessions composing the Workshop held at ciudad de La Plata on October 4-6, 2017

09/10/2017

Scientific Committee

Participation of E. Zarza in the yearly meeting of Thematic Network Coordinators of the Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), organized by CYTED and held in Lisboa, Portugal.

19/10/2017

Dissemination and divulgation

Participation of Sixto Malato in “Jornadas de Transferencia y Divulgación Científica 2017” organized by Grupo de Tratamiento de Aguas de la Universidad de Extremadura and held in Ámbito Cultural de El Corte Inglés de Badajoz (Spain).

23/10/2017

Technical Visit and Meeting

Visit to PSA of the company Consultores y Contratistas Generales SAC (CONSULCONT) of Perú to discuss potential collaborations.

06/11/2017

Lecture

Invited lectures on "*Centrales Termosolares: temas porioritarios de I+D*" and "*Experiencia Española con las Centrales Termosolares*" of Eduardo Zarza at the **Jornada sobre hibridación solar, biomasa y residuos**, organized by the Engineering School of University of Seville (Spain)

14-15/11/2017

Technical Visit and Meeting

The final meeting and steering committee of SFERA-II project (coordinated by Isabel Oller) was celebrated at PSA, including working sessions and technical visit to the facilities.

14-16/11/2017

Lecture

Invited lectures on: ***"Thermochemical Storage", "Phase Change Materials", "Latent storage: general concepts and integration in a STE plant Energy Storage", "Modelling of single tank packed bed thermocline TES", "Thermoclines: general concepts and integration in a STE plant Energy Storage"*** of Rocio Bayón and Esther Rojas in the Annual Autumn School on Concentrated Solar Technologies (CST), organized by the Cyprus Institute at Nicosia, Cyprus.

15/11/2017

Technical visit

A Delegation composed by a group of representatives of official institutions and organisms related to the energy sector from several countries (Argentina, Brazil, Chile, México and Morocco), invited by the EXTENDA Regional Agency of Andalucia, visited PSA facilities to receive information about ongoing research activities on CSP technologies.

20/11/2017

Technical visit

A high level Delegation from Jordan, headed by members of the Ministry of Energy (MEMR) and accompanied by representatives of the World Bank and the International Finance Corporation (IFC), visited the PSA installations receiving detailed information about the experimental facilities and the state of art on CSP technologies.

21/11/2017

Technical visit

The PSA hosted the visit of a Delegation from IRESEN, Morocco, invited by the Department of Foreign Technology Action of CDTI in the frame of the ongoing international cooperation, with the aim of improve the capabilities of specialists on renewable energy technologies and applications.

21/11/2017

Lecture

Invited lecture on "***Participación de la Plataforma Solar de Almería en el desarrollo nacional de las tecnologías solares térmicas de concentración*"** of Eduardo Zarza at the V Workshop Internacional sobre Calor de Processo Industrial e Usinas Solares Termoelétricas, organized by the Brazilian university of Pernambuco at Recife on November 20-22, 2017.

Audience of the V Workshop Internacional sobre Calor de Processo Industrial e Usinas Solares Termoelétricas

24/11/2017

Lecture

Invited lecture on "***El almacenamiento térmico y sus aplicaciones*"** of Rocio Bayón at University of Valladolid, Spain

30/11/2017

Lecture

Invited lecture on "**Centrales Termosolares: potencial comercial y mejoras tecnológicas"** of Eduardo Zarza at Autonomous University of Madrid (UAM)

07/12/2017

Lecture

Invited lecture of Inmaculada Polo on the Photocatalytic and Superhydrophilic Surfaces Workshop: "Solar water purification and reuse: new photocatalytic materials and pilot plants experiences" in the Museum of Science and Industry, Manchester (Reino Unido).

22/12/2017

Social Act

The Director of PSA, Julián Blanco, invited to all the personnel to the Social Act where the overall resume of R&D activities carried out along the year 2017 and the planning for next year were exposed.

9. PUBLICATIONS

PhD Thesis

1. Serrano-Aguilera, J.J. (2017). Thermal hydraulic and optical modeling of solar direct steam generation systems based on parabolic-trough collectors. (Unpublished doctoral dissertation). Universidad de Málaga, Málaga.
2. Evaluación de sistemas comerciales en espiral de destilación por membranas y su aplicación al tratamiento de aguas. Author: Alba Ruiz Aguirre.Supervisors: G. Zaragoza, José M. Fernández Sevilla. 4 July 2017.
3. Kinetic modelling of the Escherichia coli inactivation in water by solar radiation: applications to SODIS. Author: María Castro Alférez Supervisors: Pilar Fernández Ibáñez, María Inmaculada Polo López, Javier Marugán. 6 July 2017

SOLAR CONCENTRATING SYSTEMS UNIT

SCI PUBLICATIONS

1. Alonso, E., Gallo, A., Roldán, M.I., Pérez-Rábago, C.A., Fuentealba, E.. Use of rotary kilns for solar thermal applications: Review of developed studies and analysis of their potential. ***Solar Energy*** 144 (2017) Pages 90–104. Doi: http://dx.doi.org/10.1016/j.solener.2017.01.004
2. Alonso-Montesinos, J., Barbero, J., Polo, J., López, G., Ballestrín, J., Batlles, F.J. Impact of a Saharan dust intrusion over southern Spain on DNI estimation with sky cameras. ***Atmospheric Environment***. Vol. 170 (2017), pp. 279-289. ISSN: 1352-2310. https://doi.org/10.1016/j.atmosenv.2017.09.040
3. Avila-Marín, A., Fernández-Reche, J., Casanova, M., Caliot, C, Flamant, G. Numerical simulation of convective heat transfer for inline and stagger stacked plain-weave wire mesh screens and comparison with a local thermal non-equilibrium model. SolarPACES 2016. ***AIP Conf. Proceedings*** 1850 (2017), 030003. http://dx.doi.org/10.1063/1.4984346
4. Ballestrín, J., Roldán, M.I. Measuring High Surface Temperature in Concentrated Solar Radiation Environments. ***Applied Engineering***. Vol. 1, No. 2, 2017, pp. 8-18. doi: 10.11648/j.ae.20170102.11
5. Ballestrín, J., Roldán, M.I. Contact sensors for measuring high surface temperature in concentrated solar radiation environments. ***Measurement*** 109 (2017) 65-73. ISSN: 0263-2241
6. Ballestrín, J., Roldán, M.I. Measuring High Surface Temperature in Concentrated Solar Radiation Environments. ***American Journal of Engineering and Technology Management***. Vol. 2, No. 3, 2017, pp. 25-35. doi: 10.11648/j.ajetm.20170203.12. ISSN: 2575-1948 (Print); ISSN: 2575-1441 (Online).
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8. Biencinto, M., Montes, M.J., Valenzuela, L., González, L. Simulation and comparison between fixed and sliding-pressure strategies in parabolic-trough solar power plants

with direct steam generation. ***Applied Thermal Engineering*** 125 (2017), 735-745. http://dx.doi.org/10.1016/j.applthermaleng.2017.07.059.

9. Bonilla, J., de la Calle, A., Rodríguez-García, M.M., Roca, L., Valenzuela, L. Study on shell-and-tube heat exchanger models with diferente degree of complexity for process simulation and control design. ***Applied Thermal Engineering*** 124 (2017), 1425-1440. http://dx.doi.org/10.1016/j.applthermaleng.2017.06.129
10. Bonilla J, Rodríguez-García M-M, Roca L, de la Calle A, Valenzuela L, Design and experimental validation of a computational effective dynamic thermal energy storage tank model, Energy (2017), doi: 10.1016/j.energy.2017.11.017.
11. Bouaddi, S., Ihlal, A., Fernández-García, A. Comparative analysis of soiling of CSP mirrors materials in arid zones. ***Renewable Energy*** **101** (2017), 437-449. http://dx.doi.org/10.1016/j.renene.2016.08.067.
12. Cundapí, R., Moya, S.L., Valenzuela, L. Approaches to modeling a solar field for direct generation of industrial steam. ***Renewable Energy*** **103** (2017), 666-681. http://dx.doi.org/10.1016/j.renene.2016.10.081.
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BOOK CHAPTERS

1. Fernández-García, A., Sutter, F., Fernández-Reche, J., Lüpfert, E. The Performance of Concentrated Soalr Power (CSP) Systems. Analysis, Measurement and Assessment. Part One: CSP Component Performance. Cap. 3: Mirrors. Woodhead Publishing Series in Energy (edited by Peter Heller). Elsevier. Cambridge, 2017.
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PRESENTATIONS AT CONGRESSES

<u>Oral presentations</u>

1. Bayón, R., Biencinto, M, Rojas, E., Uranga, N. Study of Dry Cooling Systems for STE Plants Based on Latent Storage. ***Enerstock 2018***, 25-28 April, 2018, Adana (Turkey)
2. Burisch, M., Sanchez, M., Olano, X., Olarra, A., Villasante, C., Olasolo, D., Monterreal, R., Enrique, R., Fernández-Reche, J. Scalable HeliOstat CalibRation SysTem (SHORT). How to

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7. García-Segura, A., Fernández-García, A., Ariza, M.J., Sutter, F., Valenzuela, L. Investigations on primary reflectors for solar thermal applications exposed to corrosive atmospheres. ***EUROMAT 2017 – European Congress and Exhibition on Advanced Materials and Processes***. 17-22 September, 2017. Thessaloniki, Greece.
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11. Sallaberry, F., Valenzuela, L., López-Martín, R., García de Jalón, A., Perez, D. Receiver tube heat losses model for standardized testing. ***23rd SolarPACES Conference***, September 26-29, 2017. Santiago, Chile.
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SCI PUBLICATIONS

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1. G. Zaragoza, A. Ruiz-Aguirre, J.A. Andrés-Mañas, P.A. Davies. Modeling spiral-wound commercial modules for applications of membrane distillation. Oral presentation. 3rd International Conference on Desalination using Membrane Technology. Gran Canaria (Spain), 2-5 April 2017.
2. J.A. Andrés-Mañas, P. Palenzuela, D.C. Alarcón-Padilla, F.G. Acién, G. Zaragoza. Membrane distillation for the treatment of high-salinity aqueous solutions in the regeneration of salinity gradient resources. Oral presentation. Euromed 2017: Desalination for Clean Water and Energy: Cooperation around the World. Tel Aviv (Israel), 9-12 May 2017.
3. P. Palenzuela, D.C. Alarcón-Padilla, G. Zaragoza. Multi-effect distillation for regeneration of saline solutions used in a RED close-loop process. Oral presentation. Euromed 2017: Desalination for Clean Water and Energy: Cooperation around the World. Tel Aviv (Israel), 9-12 May 2017.
4. G. Zaragoza, J.A. Andrés-Mañas, A. Ruiz-Aguirre. Membrane distillation at industrial scale: state of the art of current modules. Invited oral presentation. 5th International Scientific Conference on Pervaporation, Vapor Permeation and Membrane Distillation. Torun (Poland), 20-23 June 2017. 1O224

5. Bonilla, J., Carballo, J. A., Roca, L., & Berenguel, M. (2017). Development of an open source multi-platform software tool for parameter estimation studies in FMI models. In 12th International Modelica conference 2017 (pp. 683-692). 15-17 May 2017, Prague, Czech Republic.
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7. J. D. Gil, L. Roca, A. Ruiz-Aguirre, G. Zaragoza, J. L. Guzman, and M. Berenguel, "Using a Nonlinear Model Predictive Control strategy for the efficient operation of a solar-powered membrane distillation system". Oral presentation. 25th Mediterranean Conference on Control and Automation, MED 2017. Valletta (Malta), 3-6 julio 2017.
8. J. D. Gil, L. Roca, M. Berenguel, A. Ruiz-Aguirre, and G. Zaragoza, "Control predictivo para la operación eficiente de una planta formada por un sistema de desalación solar y un invernadero". Poster. XXXVIII Jornadas de Automática, Gijón, 6-8 septiembre 2017.
9. G. Zaragoza. Comparative analysis of commercial MD modules based on flat sheet membranes. Invited oral presentation. 2nd International Symposium on Innovative Desalination Technologies. Gyeongju (Corea del Sur), 20-21 September 2017.
10. T. Orth, D.C. Alarcón-Padilla, G. Zaragoza, P. Palenzuela, P. Mueller. Shaping the future of thermal desalination with high performnace heat conducting polymer tubes. Oral presentation. IDA World Congress 2017: Water Reuse and Desalination. Sao Paulo (Brasil), 15-20 October 2017.
11. G. Zaragoza, J.A. Andrés-Mañas, A. Ruiz-Aguirre. State of the art of membrane distillation at industrial scale. Invited oral presentation. 2017 EU-China Workshop on Research and Application of Membrane - Membrane Systems for Water Treatment and Reuse. Weihai (China), 17-18 November 2017.
12. Campos, E., Molina, F., Terrero, P., Zarzo, D., Calzada, M., Cano, J.L., Palenzuela, P., Alarcón-Padilla, D.C. Development of an innovative and efficient system for solar desalination with Zero Liquid Discharge (ZLD). The International Desalination Association World Congress on Desalination and Water Reuse 2017. Sao Paulo, Brazil, October, 15-20, 2017. IDAWC REF: 17WC-58231.
13. Ortega-Delgado, B., Palenzuela, P., Alarcón-Padilla, D.C. Yearly simulations of the electricty and fresh water productions in PT-CSP+MED-TVC plants: Case study in Almería (Spain). Oral Presentation. SolarPACES 2017.Solar Power & chemical Energy Systems. Santiago de Chile (Chile). September, 26-29, 2017.
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1. Palenzuela, P., G. Zaragoza, B. Peñate, V. Subiela, D.C. Alarcón-Padilla and L. García-Rodríguez. The use of solar energy for small-scale autonomous desalination. En: “Renewable energy technologies for water desalination”; Eds: Mahmoudi, Ghaffour, Goosen, Bundschuh; CRC Press/Balkema Taylor & Francis Group; 2017. ISBN: 9781138029170.
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WATER SOLAR TREATMENT UNIT

DISSERTATIONS

1. Perez-Estrada L. Fingerprinting indigenous organic pollutants and its degradation products using UPLC-ESI-Ion-Mobility (T-wave)/TOF-MS. Agilent Ion Mobility Spectrometry Seminar. Manchester (UK), January 12th, 2017.
2. Perez-Estrada L. Testing performance of the separation potential of the SelexIon (FAIMS) in a 6600 Triple-TOF/MS for untreated complex samples. AB Sciex, Warrington (UK), May 24th-26th, 2017.
3. Malato S. Ponencia en “Workshop & NIS colloquium. Keywords: environment, water, sustainable materials, circular economy. Towards 2018-20 European proposals”. Università di Torino – Dipartimento di Chimica, 20-21 April 2017.
4. Malato Rodríguez, S. Treatment of CECs by solar driven AOPs. 2nd Summer School on Environmental Applications of Advanced Oxidation Processes and Training School on Advanced Treatment Technologies and Contaminants of Emerging Concern. Biblioteca Municipal Almeida Garrett, Porto, Portugal. July 10th -14th, 2017.
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1. Malato S., Oller I., Miralles-Cuevas S., Maldonado M.I., Perez-Estrada L. Different applications of solar photo-Fenton process: economical approach and comparison with other AOPs. 5th European Conf. on Environmental Appl. of Advanced Oxid. Proc. (EAAOP5), 25-29 June, 2017, Prague (Czech Rep.) Book of Abstracts Pag. 48. Keynote (KL6).
2. Polo-López M.I., Maldonado Rubio M.I., Pérez-Estada L., Oller Alberola I., Malato Rodríguez S. Solar water purification and reuse: new photocatalytic materials and pilot plants experiences. Photocatalytic and Superhydrophilic Surfaces Workshop PSS2017. Museum of Science and Industry, Manchester, Reino Unido. 7-8 Diciembre 2017. Invited oral.

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1. Malato S. Treatment of contaminants of emerging concern: applications by Solar AOPs and combination with other technologies. 3rd Iberoam. Conf. on Adv. Oxid. Tech.. (III CIPOA). November 14th-17th, 2017, Guatape (Colombia). Plenary lecture.

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1. M.J. Jiménez. "Guidelines to dynamic analysis. Different approaches and physical aspects". Presented at DYNASTEE Summer School 2017 on Dynamic Calculation Methods For Building Energy Assessment DYNASTEE-INIVE and the School of Architecture (University of Granada, Spain), in collaboration with CIEMAT (Spain), DTU (Lyngby, Denmark) and ESRU (Strathclyde University, Glasgow, UK). 3-7 July 2017. Granada (Spain).
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