GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

PLATAFORMA SOLAR DE ALMERÍA

Plataforma Solar de Almería

Largest European research centre devoted to solar thermal and photochemical technologies

Table of contents

List of figures

List of tables

1 General Presentation

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

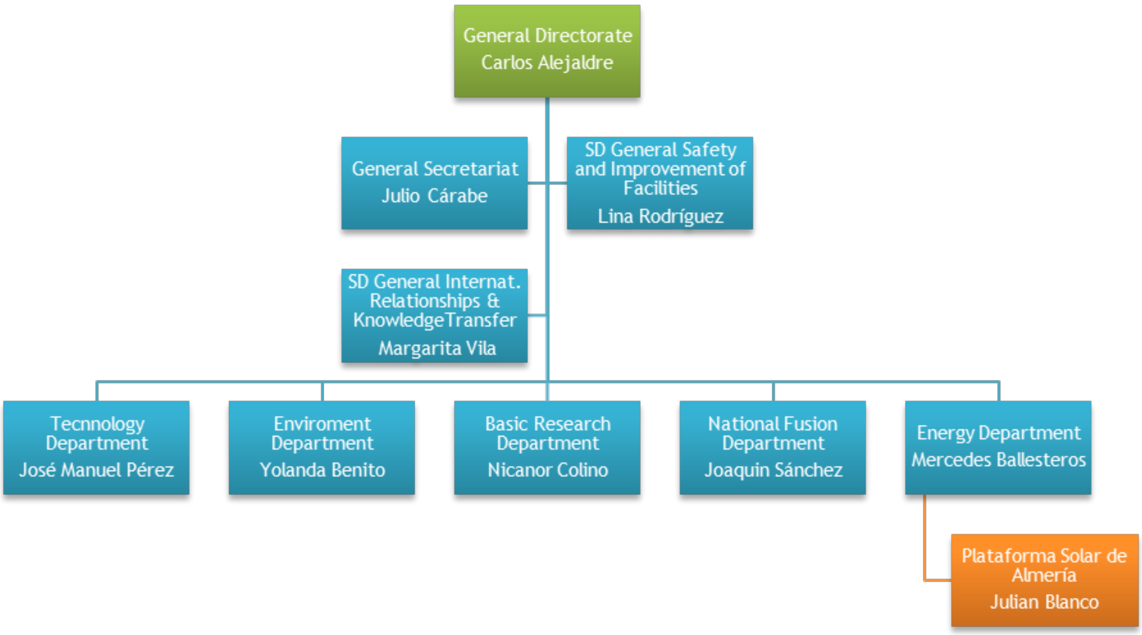


Figure 1. Integration of the PSA in the CIEMAT organization.

The following goals inspire its research activities:

- Contribute to establish 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 international technological cooperation, especially in the Mediterranean Area.
- Assist industry in identifying solar thermal market opportunities.

Since 2021, research activity at the PSA has been structured around seven R&D Units under a Technical Coordinator, plus a strong unit to manage and also coordinate all facilities and laboratories, namely the PSA Management Unit. In addition to the different horizontal services (IT services, Instrumentation, Maintenance, Civil Engineering, Operation, etc.), two additional facilities (METAS and LECE), physically allocated within PSA but with associated personnel formally outside PSA structure, are also included in this PSA Management unit.

Figure 2. Aerial view of the PSA.

The seven R&D Units are as follows:

- Linear Focusing concentrating solar thermal technologies. Devoted to testing, evaluating and developing components and applications for linear focusing solar concentrators.
- Point Focusing concentrating solar thermal technologies. Target is focused on providing technical assessment to the industry stakeholders together with the research and innovation related to power tower technologies such as the measurement of concentrated solar flux, R&D of new fluids and receivers, and the optical analysis.
- Thermal Energy Storage for concentrating solar thermal technologies. Addressing the design, testing and optimization of thermal storage systems for temperatures above 100˚C.
- Materials for concentration solar thermal technologies. Addressing the development and testing of new or improved materials for CST solar technologies or their applications, as well as thermal treatment, aging or modification of materials.
- Thermochemical Processes to Solar Fuels and Raw Materials Production. This includes high temperature processes based on concentrated solar energy to produce hydrogen and other valuable and energy intensive raw materials.
- Solar Thermal Applications. Devoted to the development and evaluation of applications of solar thermal technology for industrial processes, including desalination and brine concentration.

- Solar Treatment of Water. Focused on exploring the chemical possibilities of solar energy, especially the potential for water decontamination and disinfection and the production of solar fuels through photochemical processes.

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

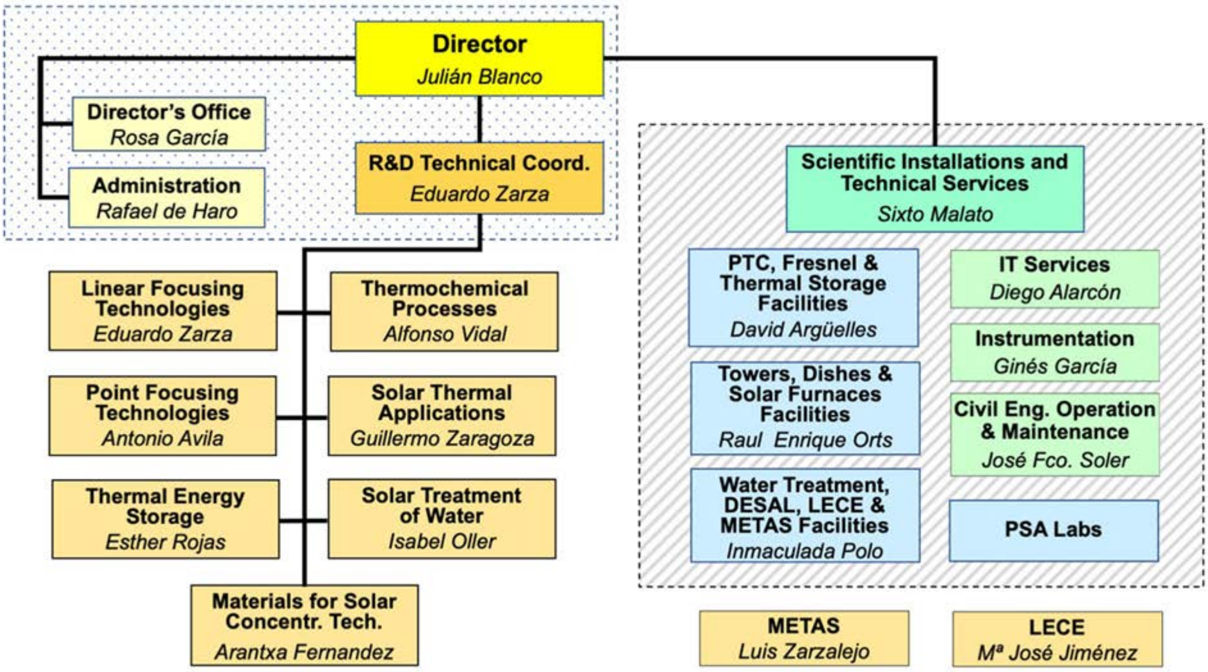


Figure 3. Internal organizational structure of PSA in 2021.

The scientific and technical commitments of the PSA and the workload this involves are undertaken by a team of 134 people that since December 2020 make up the permanent staff lending their 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 122 people who work daily for the PSA, 65 are CIEMAT personnel, 13 of whom are located in the main offices in Madrid.

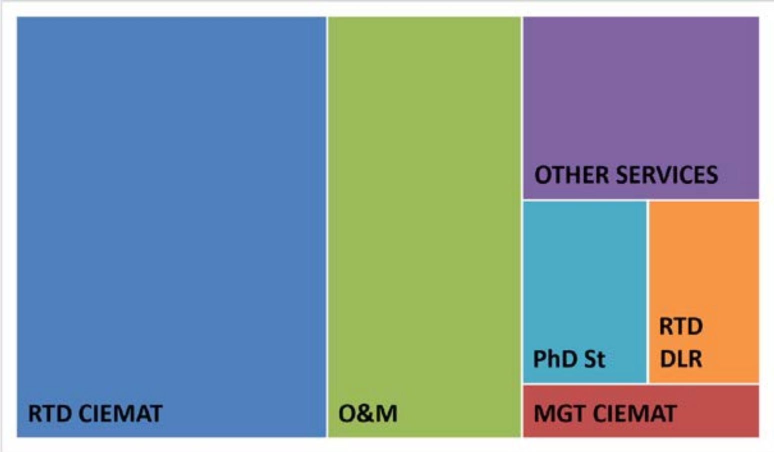


Figure 4. Distribution of permanent personnel at the PSA as of December 2020.

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

The rest of the personnel is made up of a non-less important group given the centre's characteristics. This is the personnel working for service contractors in operation, maintenance and cleaning in the different facilities. Of these 32 people, 15 work in operation, 13 in maintenance and 4 in cleaning. The auxiliary services contract is made up of 5 administrative personnel and secretaries, 7 IT technicians for user services, and another 5 people from the security contract, which makes a total of 17 people.


Figure 5. PSA staff in 2020.

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 a greater success assurance.

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.

2 Facilities and Infrastructure

2.1 Parabolic Trough Systems

2.1.1 The DISS experimental plant

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

The facility (see Figure 6 and Figure 7) consists of two subsystems, the solar field of parabolic trough collectors and the balance of plant (BOP). In the solar field, feed water is preheated, evaporated and converted into superheated steam at a maximum pressure of 100 bar and maximum temperature of 500°C as it circulates through the absorber tubes of a 1000 m long row of parabolic trough collectors with a total solar collecting surface of 3,838 m^2. The system can produce a nominal superheated steam flow rate of 1 kg/s. In the balance of plant, this superheated steam is condensed, processed and reused as feed water for the solar field (closed loop operation).

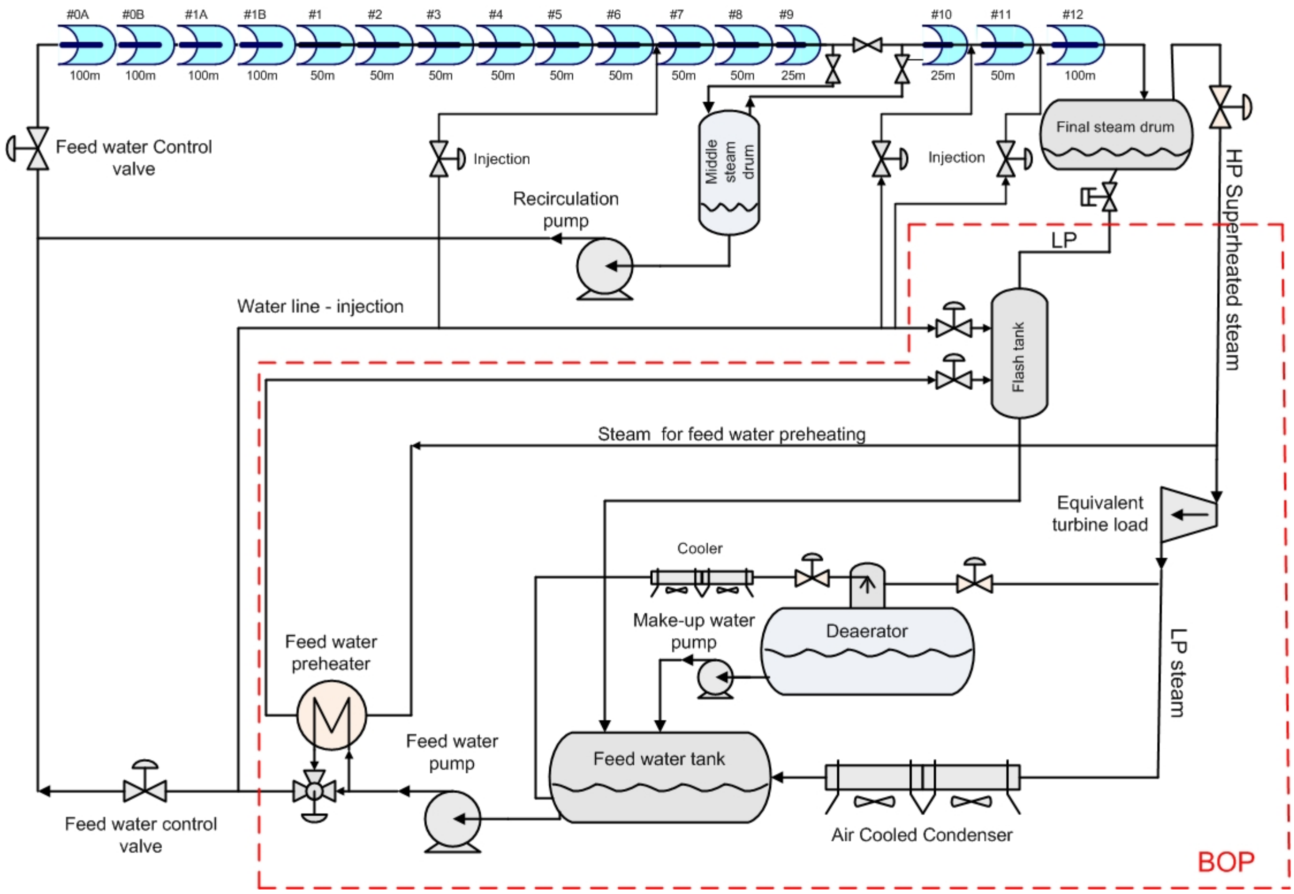


Figure 6. Simplified flow diagram of the PSA DISS loop.

Facility operation is highly flexible and can work from low pressures (≈ 30 bar) up to 100 bar. It is also equipped with a complete set of valves allowing the solar field to be configured for Recirculation (perfectly differentiated evaporation and superheating zones), for Once-Through (the intermediate water-steam separator and the recirculation pump located in the solar field are not used in this operating mode) and 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 different 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 is recorded.

Figure 7. View of the DISS plant solar field in operation.

Among the capacities associated with this facility are the following:

- Component testing for parabolic-trough collector solar fields with direct steam generation (DSG) in their receiver tubes (receivers, ball joints or flex holes, 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 flow of water/steam in horizontal tubes with non-homogeneous heat flux.

2.1.2 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 the following components:

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

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

The facility consists of a closed thermal-oil circuit connected to three 75-m long solar collectors connected in parallel, being able to operate only one at a time (see simplified diagram of the facility in Figure 8). The east-west rotating axis of the solar collectors increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The thermal oil used in this facility (Syltherm 800®) has a maximum working temperature of 400°C and a freezing point of 40°C.

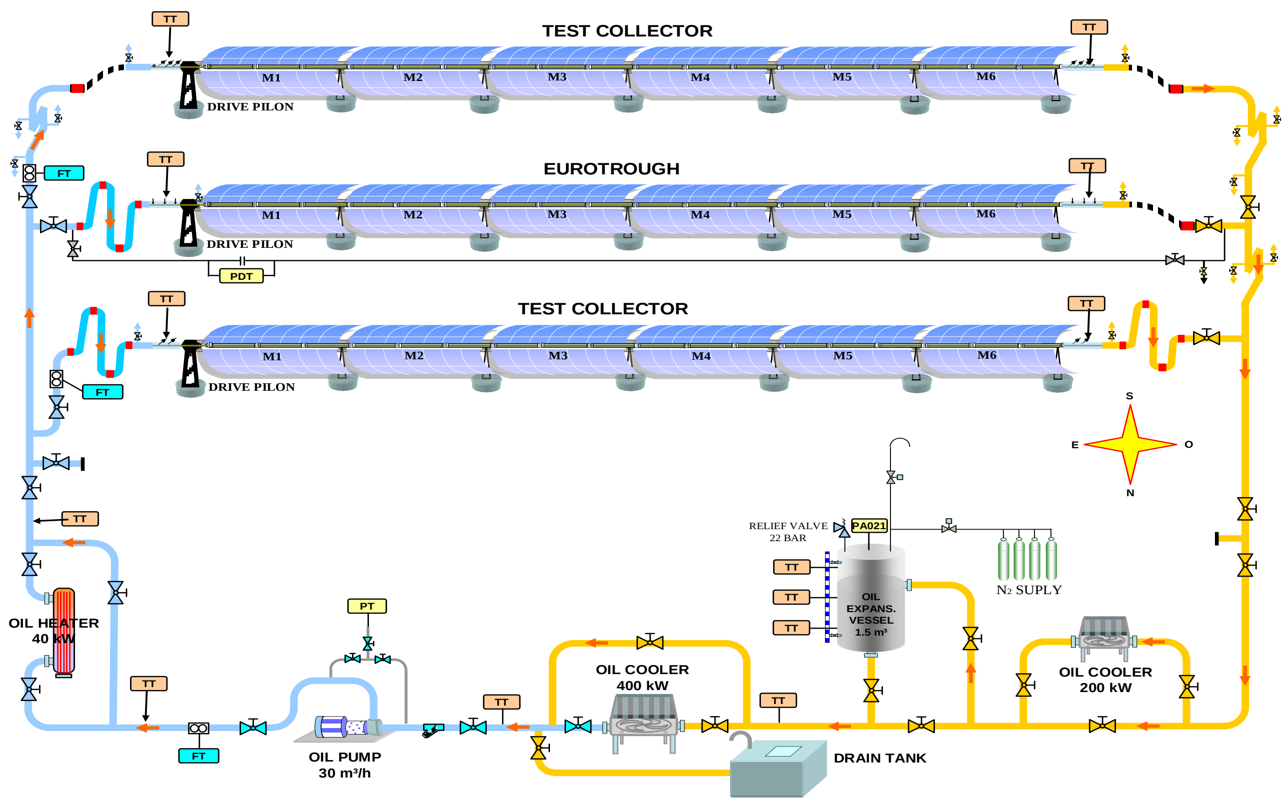


Figure 8. Diagram of the HTF test Loop located at the PSA.

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

- 1-m^3-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 a European consortium with the financial aid of the European Commission was installed and evaluated under real working conditions at this facility in 1998. After its evaluation, this collector prototype 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.

2.1.3 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 PSA. It was designed and erected by the company *Iberdrola Ingeniería y Sistemas* in 2010 starting the test campaign throughout the following year. The pilot plant was transferred to CIEMAT to be used as testing loop.

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

The collector's modules are connected to the balance of plant (BOP) in parallel or in series configuration using the ad hoc valves. A pump circulates the silicone heat transfer fluid (SHTF) with a mass flow similar to that of commercial power plants. Mass flow is measured directly using Vortex flowmeter and differential pressure flowmeter types. A controlled air cooler unit dissipates the collected thermal energy and ensures a constant HTF temperature (±1 K) at the inlet of the collector field. 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 9. View of the PROMETEO test facility.

2.1.4 The Parabolic Trough Collector Test Loop (PTTL) facility

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

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

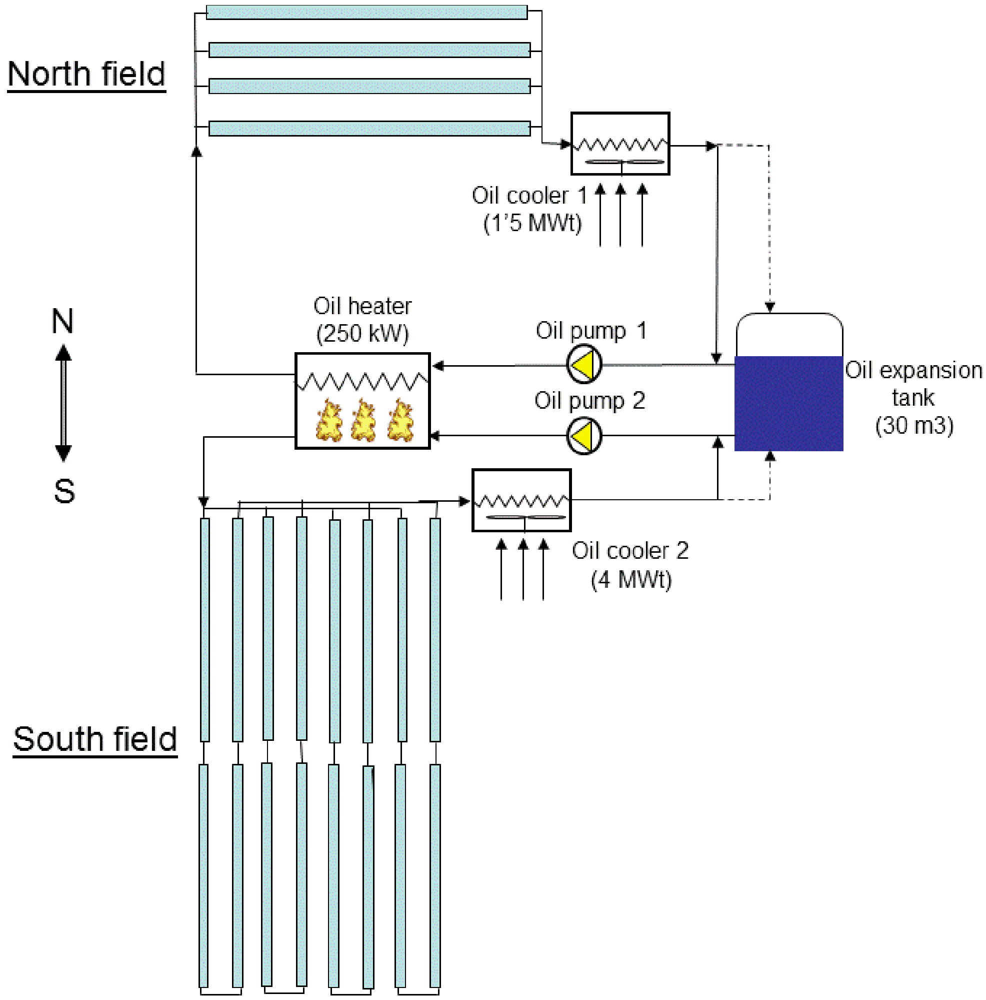


Figure 10. Simplified scheme of the PTTL facility

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

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

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

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

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

2.1.5 NEP: The facility for Polygeneration Applications

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

The purpose of this facility is the preliminary study of the behaviour of a parabolic trough solar field of small concentration ratio, the determination of its feasibility as a heat source in polygeneration schemes, in particular in CSP+D (i.e., electricity generation + water desalination) requiring temperatures around 200°C. The solar collector selected was the Polytrough 1200 prototype by NEP Solar. It has a production of 15.8 kW per module (0.55 kW/m^2) under nominal conditions, with a mean collector temperature of 200°C, and an efficiency over 55% in the range of 120-220°C (for 1,000 W/m^2 of direct normal irradiance).

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

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

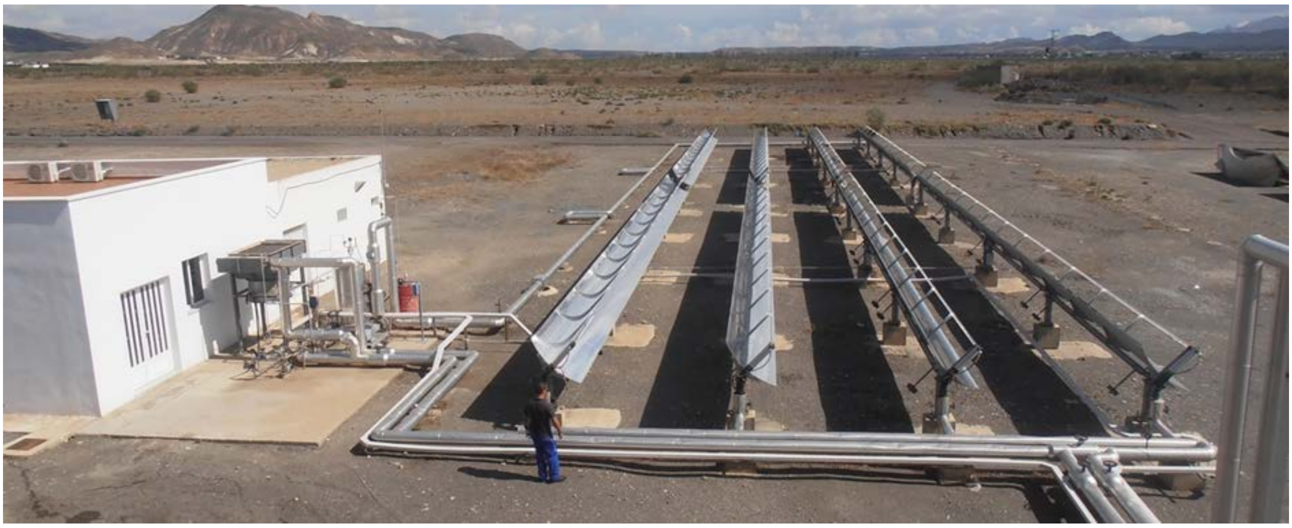


Figure 11. NEP PolyTrough 1200 solar field.

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

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

The experimental test loop (see Figure 12) is located north of the DISS experimental plant control building, which also houses necessary the equipment for the control and data acquisition of this experimental test loop.

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

- Two East-West-oriented EUROtrough parabolic-trough collectors, each 50 m long with a 274.2-m^2 collector surface. The collectors 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 necessary gas flow rate 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 test loop piping with the gas used as heat transfer fluid.

Since testing at 400°C was successfully completed at the end of 2009, this facility was then upgraded to achieve temperatures of up to 515°C 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 515°C 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 12. View of the IFL experimental facility (with parabolic troughs) using compressed gas as heat transfer fluid.

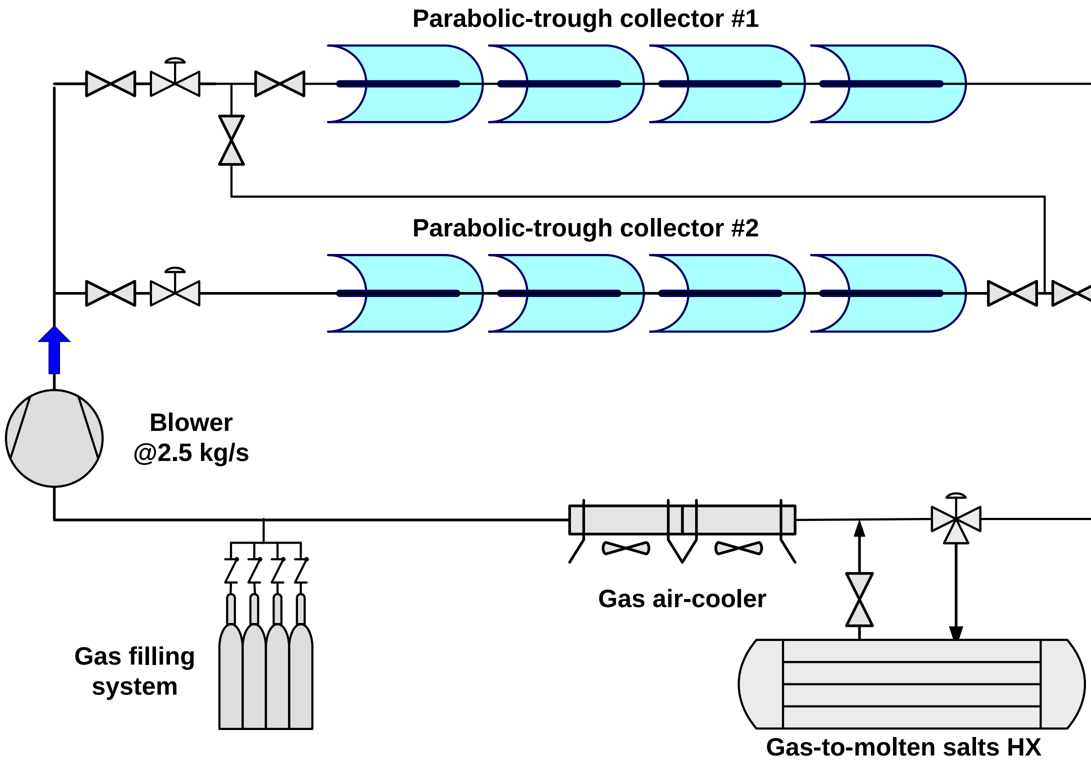


Figure 13. Simplified system diagram of the IFL experimental facility located at the PSA.

2.1.7 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 m^3 of Santotherm-55 thermal oil.

The solar field is composed of six parabolic-trough collectors, model TCP-100, installed in three parallel loops, with two collectors in series within each loop, see Figure 14. Each collector is composed of eight parabolic trough modules with a total length of 100 m and a parabola width of 5.77 m. The total solar collecting surface of each collector is 545 m^2. The focal distance is 1.71 m, the geometrical intercept factor is ≥0.95, and the peak optical efficiency is 77.5%. The receiver tubes used in this solar field were delivered by Archimede Solar Energy (Italy) and the working fluid is Syltherm®800.

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

This test facility is specially designed to perform studies related to control systems for parabolic trough solar fields. This is the reason why two collector loops are provided with the solar tracking system developed by PSA, while the third loop is provided with a commercial solar tracking system with continuous movement.

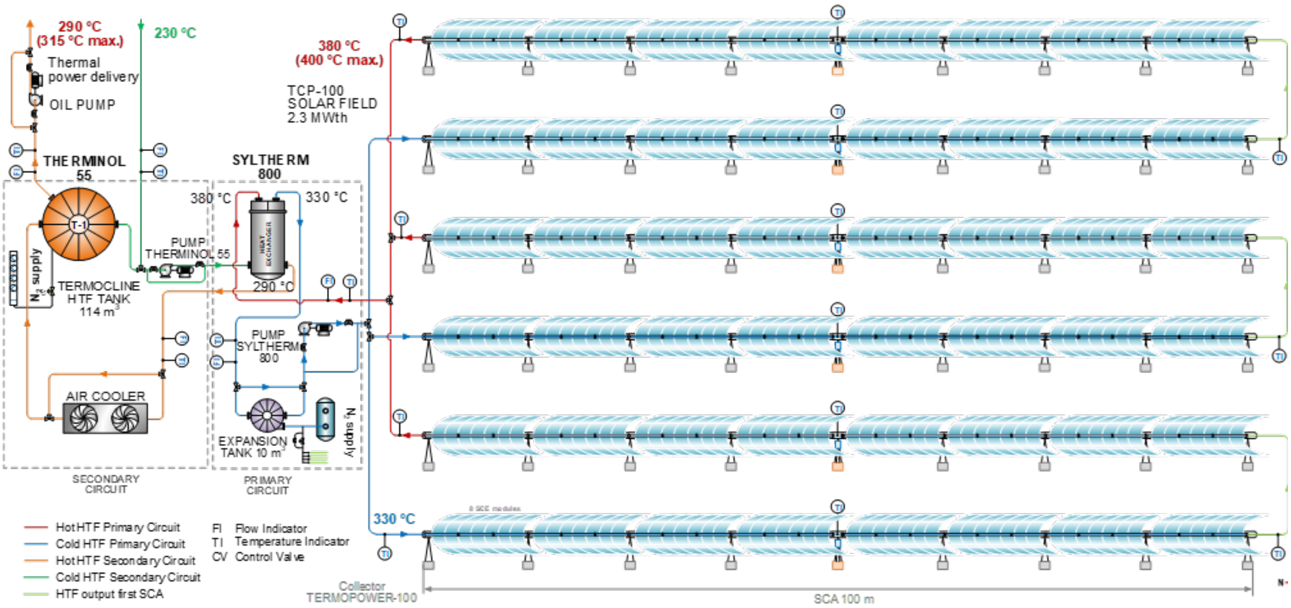


Figure 14. Diagram of the TCP-100 2.3 MWth parabolic-trough facility

2.2 Other Component Test Systems for Parabolic Trough Technology

2.2.1 KONTAS: Rotary test bench for parabolic trough systems

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

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 allows tracking at any desired angle of incidence of the solar radiation. It is equipped with high precision instrumentation and controls for accurate, 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 collector rows in commercial plants. Mass flow is measured directly using the Coriolis measuring principle avoiding uncertainties of the density. The heating and cooling unit dissipate the energy the hot HTF collects on the way through the receiver tube of the collector module mounted on the rotating platform and ensures a constant HTF temperature (±1 K) at the inlet of the collector. Sensors for measurement of inlet and outlet temperatures are highly precise and may be calibrated on site. A high precision meteorological station delivers accurate radiation and wind data.

Figure 15. Side view of KONTAS test bench and the heating/cooling unit (right side).

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

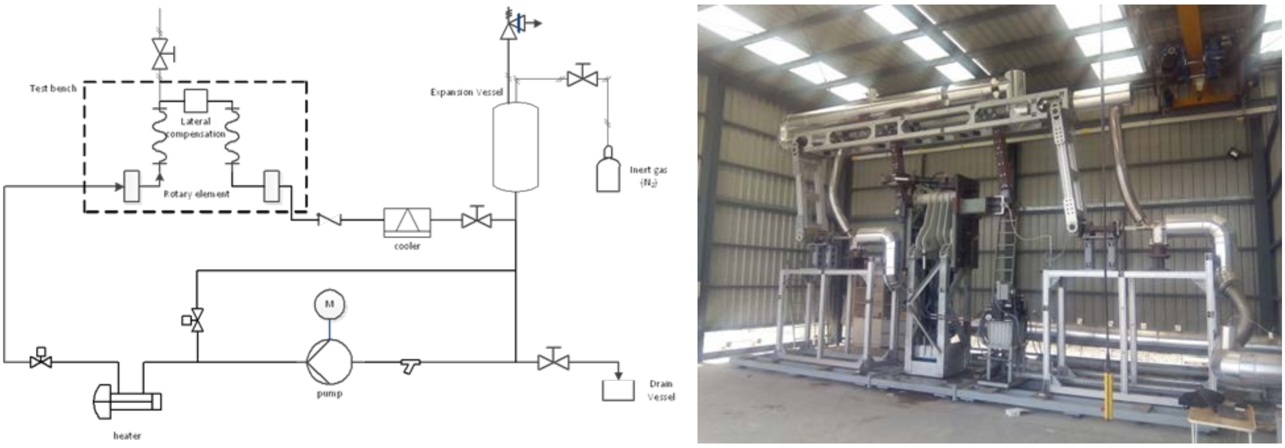
The REPA test facility is the result of merging CIEMAT's activities in Task 14.4 of the European project SFERA-II (finished in 2017) and DLR's activities within the national German project StaMeP. The facility is now used by CIEMAT and DLR in the framework of a joint collaboration.

The test bench is divided into two functional sections, the so-called kinematics unit, to hold and move the pieces REPAs to be tested, and the balance of plant unit for supplying the conditioned heat transfer fluid (see Figure 16.a).

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

The kinematics unit (see Figure 16.b) is prepared to accommodate test samples of ball joints and flexible hoses with varying and adjustable geometries, e.g., focal lengths. It is prepared to accomplish both rotational and translational movements with the following characteristics:

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



(a) (b)

Figure 16. Schematic diagram of the REPA test loop at PSA (a) and north view of the test facility with two flex-hoses mounted for testing (b).

2.2.3 The FRESDEMO Loop

The FRESDEMO loop is a “Linear Fresnel concentrator” technology pilot demonstration plant. This 100 m long, 21 m wide module has a primary mirror surface of 1433 m^2, 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 qualities, pressures and temperatures for testing in the three working modes: preheating, evaporation and superheating.

Figure 17. Photo of the linear Fresnel concentrator erected at the PSA.

2.3 Thermal Storage Systems

2.3.1 Molten Salt Test Loop for Thermal Energy Systems

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

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

- Checking of components (pumps, flowmeters, etc.) for their use in a liquid molten salt medium.
- Optimization of procedures in normal operation for a two-tank system configuration.

- Optimization of procedures in risk situations for a two-tank system configuration. Designing recovery procedures.
- Validation of models and simulation approaches for molten salt thermal systems.
- Characterization of heat exchangers for molten salt/oil.
- Characterization of thermocline tanks.

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

Figure 18. Molten Salt (MOSA) outdoor test loop.

BES-II, an indoor installation at the PSA, is especially designed for the testing of valves, pressure transmitters and other small molten salts components under real working conditions up to 600°C and 40 bar. Components with nominal diameters from 2” up to 6” can be tested on this test bench.

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

Figure 19. MOSA indoor test bench (BES-II).

2.3.2 Atmospheric Air Packed Bed Test Bench

This facility is an insulated storage tank of around 0.1 m^3 where different packed bed configurations and materials can be tested using atmospheric air as heat transfer fluid. Provided with a maximum electric power of 15 kW, a charge process with air up to 900°C is possible. Thermocouples along its length and at different radial positions give an accurate map of temperature of the packed bed.

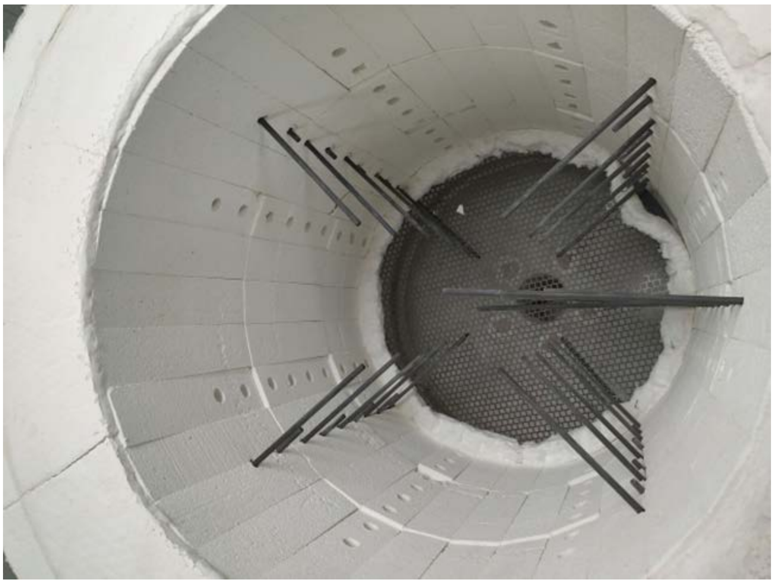


Figure 20. Picture taken from the top of the tank, showing its internal room and thermocouples at different lengths and radial positions.

Figure 21. Researcher adjusting some items from the upper top of the tank.

For more information see E. Alonso, E. Rojas, R. Bayón, 2020, Packed-bed thermocline testing facility with air as HTF for sensible thermal energy storage, Eurosun 2020 Congress

2.4 Central Receiver Systems

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

2.4.1 The 6 MWth CESA-I Plant

The CESA-I plant (see Figure 22) 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-I 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 22. The CESA-I facility seen from the north.

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

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 MW_{th} at a typical design irradiance of 950 W/m^2, achieving a peak flux of 3.3 MW/m^2. 99% of the power is focused on a 4 m circle diameter and 90% in a 2.8 m circle.

Currently, the solar extinction measurement is available on-line in the control room of the CESA-I facility at PSA, facilitating the daily operation tasks (Figure 23). Note that this is the first time that it occurs in a solar tower plant. The extinction measurement system has been developed by CIEMAT at PSA and it works taking simultaneous images of the same Lambertian target at very different distances using two identical optical systems with suitable digital cameras, lenses and filters.

Currently there is an airborne particle counter in operation whose measurement is of interest for studies of solar extinction, soiling and evaluation of volumetric receivers.

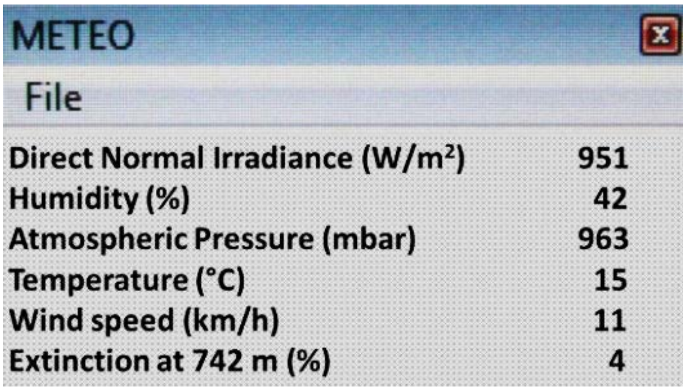


Figure 23. On-line measurement of the solar extinction in the control room of CESA-1 facility at PSA.

2.4.2 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 dedicated to testing small solar receivers in the 200 to 500 kW_{th} capacity range.

The heliostat field is composed of 91 39.3-m^2 first generation units manufactured by Martin-Marietta. The original SSPS-CRS heliostat field was improved several years ago with the conversion of all its heliostats into completely autonomous units powered by photovoltaic energy, with centralized control communicated by radio using a concept developed and patented by PSA researchers (Figure 25). This first autonomous heliostat field, which requires no infrastructure for 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 0,90, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m^2, the total thermal power reflected by the solar field is 2.5 MW_{th} and its peak flux is 2.5 MW/m^2. 99% of the power is collected in a 2.5 m diameter circumference and 90% in a 1.8 m circumference. The 43 m high metal tower has three test platforms. The two first ones 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 a crane and a calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers, and solar reactors for hydrogen production. The tower infrastructure is completed with a 4 TN capacity crane and a 1000 kg capacity rack elevator.

Figure 24. Aerial view of the experimental SSPS-CRS facility.

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

A hybrid heat flux measurement system to measure the incident solar power that is concentrated by the heliostat field is located at the SSPS-CRS tower. This method comprises two measurement systems, one direct and another 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 the 25 m test level, a cantilever with heat shield can be used to position a (optical or IR) camera only a few meters from the aperture.

Figure 25. An autonomous heliostat in the SSPS-CRS field.

2.4.3 AORA Solar Tower facility

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

Figure 26. General view of the AORA solar tower facility.

2.5 Solar Furnaces Installation

2.5.1 SF-60 Solar Furnace

The solar furnace SF60 consists basically of a 130 m^2 flat heliostat that reflects the solar beam onto a 108 m^2 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, the solar furnace has a test table movable on three axes, which is used to place the specimens to be tested on 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 in parallel to the optical axis of the parabolic-dish concentrator, continuously tracking the sun.

The heliostat associated with the solar furnace SF-60 consists of 117 flat facets, with 1 m^2 reflecting surface each, plus 52 flat facets of 0.25 m^2, giving a total reflective surface of 130 m^2. These facets have been designed, manufactured, assembled and aligned by PSA technicians. All facets are square in shape with a 3 mm thick Rioglass flat mirror silvered on their back (second surface mirror). Solar Furnace Technicians are also responsible of a new method of fixation of the facet on a frame that minimizes deformation of the reflecting surface. Figure 27 and Figure 28 show the heliostat installed in this solar furnace and a detail of the back side of the facet, respectively.

The parabolic concentrator is the main feature of this solar furnace, which concentrates the incident sunlight from the heliostat, multiplying the radiant energy at the focus. The concentrator of the SF60 solar furnace is composed of 462 hexagonal facets of spherical curvature with three different radii of curvature, distributed from smallest to largest from the centre to the outside of the parabola, depending on their distance from the focus.

Figure 27. HT120 heliostat in tracking.

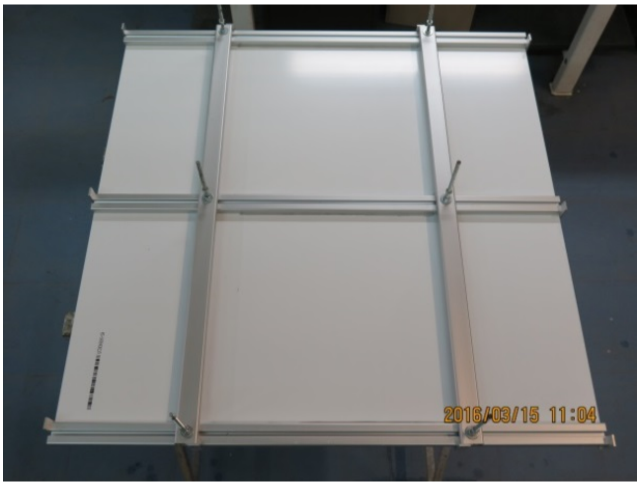


Figure 28. Back side of facet.

The shutter (attenuator), see Figure 29, consists of a set of horizontal louvers, which turn on their axis to control the amount of sunlight impacts on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter. Finally, the test table is a mobile support with movement in the three spatial axes (X, east-west; Y, north-south; Z, up-down), located under the focus of the concentrator, which is used to precisely position the test specimens to be tested at the focus. It is also used for installing the different supports and auxiliary devices necessary for carrying out the tests.

Figure 29.Shutter of the PSA SF-60 Solar Furnace.

Figure 30. Interior view of the PSA SF-60 Solar Furnace in operation.

The combination of all 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 a CCD camera hooked up to an image processor and a Lambertian target is used to measure it. The characteristics of the focus with 100% aperture and solar radiation of 1,000 W/m^2 are: peak flux, 650 W/cm^2, total power, 80 kW, and focal diameter, 20 cm.

2.5.2 SF-40 Solar Furnace

The SF-40 solar furnace consists mainly of an 8.5 m diameter parabolic-dish and a 56.5 m^2 reflecting surface, with a focal distance of 4.5 m (see Figure 31). The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive thin-glass mirrors on the front. The parabola thus formed is held at the back by a ring spatial structure to give it rigidity and keep it vertical. The new SF40 solar furnace reaches a peak concentration of 5,000 suns and has a power of 40 kW. Its focus' size is 12 cm diameter and rim angle a= 50.3°. Its optical axis is horizontal, and it is of the "on-axis" type that is parabolic concentrator, focus and heliostat are aligned on the optical axis of the parabola. In addition to the concentrator, the SF40 solar furnace includes a flat heliostat with a reflecting surface of 100 m^2, a slats shutter and a 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 of incident rays at the focus is rotated by 90° in the focal area by means of an inclined mirror with a cooling system, which is positioned in the horizontal plane. The facility is completed with a gas system and vacuum chamber -MiniVac 2-, which allows tests in controlled atmosphere and vacuum conditions, so that the specimens are not oxidized during tests.

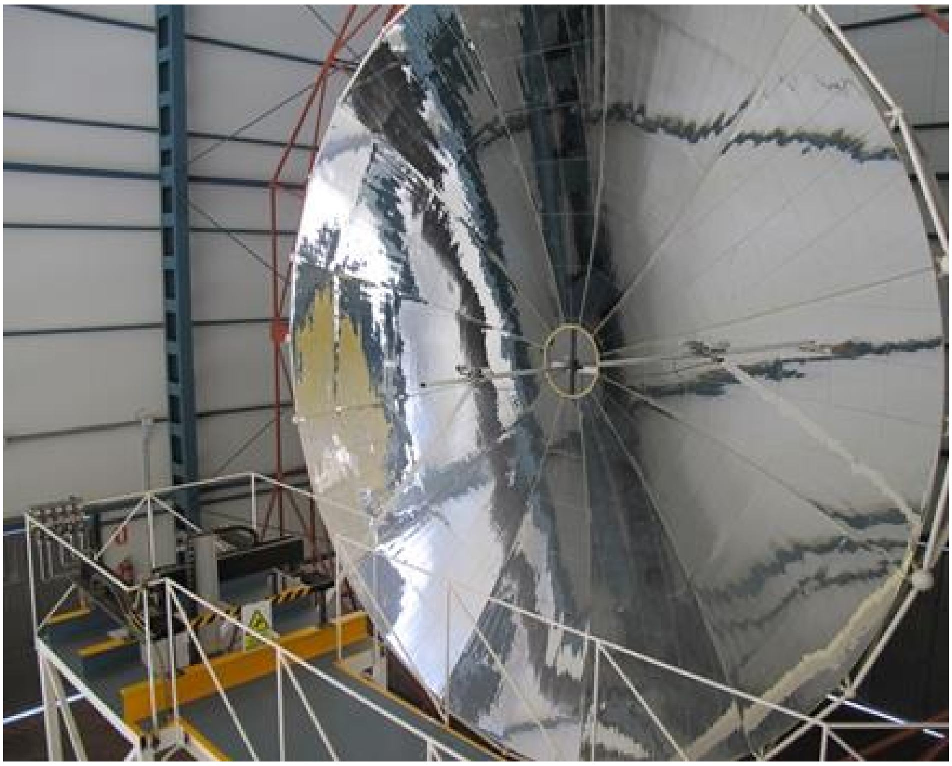


Figure 31. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

2.5.3 SF-5 Solar Furnace

Designed and built at the PSA, this system is in operation since 2012 and it is focused on tests that require high radiant flux, strong gradients, and very high temperatures. The Solar Furnace SF-5 has a power of 5-kW, it reaches concentrations above 7,000 suns, its focus diameter is 2.5 cm, and it is mainly dedicated to heat treatment of materials at high temperature, under vacuum and controlled atmosphere conditions, for which a vacuum chamber provided with a gas system is used.

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

It basically consists of an 8.7 m^2 concentrator mirror, placed upside-down with the reflecting surface facing the floor, on an 18 m high metallic tower. In the centre of the base of the tower there is a 25 m^2 flat heliostat, whose centre of rotation is aligned with the optical axis of the concentrator. At the top of the tower, in the test room, and 2 m below the vertex of the concentrator, there is a test table. Finally, under the test table and at floor level of the test room, a louvered attenuator is placed.

Figure 32. Concentrator of the SF-5 Solar Furnace.

2.6 Parabolic DISH Systems

2.6.1 EURODISH

Under the Spanish-German EUROdish Project, two new dish/Stirling prototypes were designed and erected (Figure 33), discarding the stretched-membrane technology and applying a moulded composite-material system. These parabolic dishes can be used to test new prototypes of Stirling engines, or to perform any other test requiring a focus with 50 kW_{th} maximum and a maximum concentration of 16,000 suns at the focus.

Figure 33. Front and back views of the EURODISH.

2.6.2 Accelerated ageing test bed and materials durability

This installation consists of 3 parabolic dish units, model DISTAL-II, with 50 kW of total thermal power and a two-axis sun tracking system. In the DISTAL-II dishes, the initial Stirling motors have been replaced by different test platforms to put the materials or prototypes at small scale of high concentration receivers and perform accelerated temperature cycling. With fast focusing and defocusing cycles, the probes placed at the focus of the parabolic concentrator withstand 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 receiver prototypes with or without heat transfer fluid, etc.

The three parabolic dishes DISTAL-II (Figure 34) were erected at PSA in 1996 and 1997, using the stretched membrane technology. These parabolic dishes have a diameter of 8.5 m, providing a thermal energy delivered at the focus of 50 kW_{th} at nominal insolation conditions (950 W/m^2). Its focal distance is 4.1 m, with a maximum concentration of 16,000 suns at the focus. These concentrators can be used for any experiment requiring a focus with the characteristics mentioned above (50 kW_{th} maximum and 16,000 suns peak concentration at the focus).

The test bed for durability and accelerated materials ageing is complemented with the laboratory for the assessment of the durability and characterization of materials under concentrated solar radiation existing at PSA, which is described in the laboratories section of this document (section 3.3).

Figure 34. View of a parabolic-dish DISTAL- II with the original Stirling engine.

Figure 35. Accelerated aging tests on metal tube prototypes in a parabolic-dish DISTAL- II

2.7 Experimental Solar Desalination Installations

2.7.1 Multi-Effect Distillation Facilities

2.7.1.1 Solar Multi-Effect Distillation Facility

This facility is composed of the following subsystems:

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

The multi-effect distillation unit is made up of 14 stages or effects, arranged vertically with direct seawater supply to the first effect (forward feed configuration). At a nominal 8 m^3/h feed water 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 2,326 kJ of thermal energy consumed) over 9. The saline concentration of the distillate is around 5 ppm. The nominal temperature gradient between the first cell and the last one is 40°C with a maximum operating temperature of 70°C in the first cell. The system heat transfer fluid is water, which is heated as it flows through the solar collectors and the 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.

(b)

(a) (c)

Figure 36. The PSA SOL-14 MED Plant (a) double-effect LiBr-H_2O absorption heat pump (b) and 606-m^2 flat plate solar collector field (c).

The 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.

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

2.7.1.2 Test-Bed for Solar Thermal Desalination Applications

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

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

Figure 37. The 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II).

It consists of 4 loops with 14 large-aperture flat plate collectors each (two rows connected in series per loop with 7 collectors in parallel per row), and one additional smaller loop with 4 collectors connected in parallel, all of them titled 35° south orientation. Each row has its own filling/emptying system consisting of two water deposits, from which the heat transfer fluid is pumped to the collectors at the beginning of the operation and where all the water volume in the collectors is spilt either at the end of the operation or when a temperature limit is reached (above 100°C). The solar field has flow control valves that allow having an equal distributed flow rate without further regulation. Besides, the facility has an air cooler that allows the entire energy dissipation from the solar field, which is useful for efficiency tests at different temperature levels. The five loops of collectors are connected with a thermal storage system through a heat exchanger. The thermal storage system consists of two connected water tanks with a total storage capacity of 40 m^3. This volume allows sufficient operational autonomy for the fossil backup system to reach nominal operating conditions in the desalination plant.

The 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.

2.7.2 CSP+D test facilities

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

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

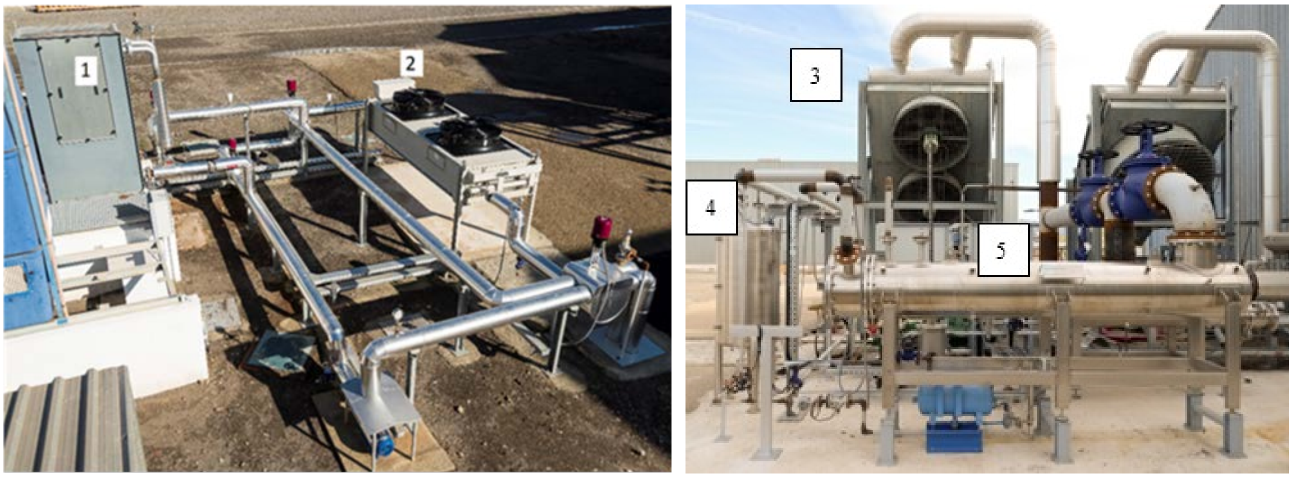
(a) (b)

Figure 38. View of the outside of the CSP+D test bed building with the air coolers (a) view of the steam ejectors in the interior of the CSP+D test bench (b).

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

2.7.2.2 Hybrid-cooling pilot plant

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



(a) (b)

Figure 39. General view of the hybrid-cooling test bed: (a) Cooling circuit: wet cooling tower (1) and air-cooled heat exchanger (2). (b) Exchange circuit: air-cooled condenser (3), condensate tank (4) and surface condenser (5).

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

2.7.3 Membrane Desalination Test Facilities

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

(a)

(b)

Figure 40. Internal (a) and external (b) 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 an 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 different commercial 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 membrane areas of 7.2 m^2 and 24 m^2 each.

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

6) Two spiral-wound modules from Trimem operating in permeate-gap configuration with total membrane areas 5.15 and 6.1 m^2.

7) Three spiral-wound modules from Aquastill operating in vacuum-enhanced air-gap configuration with membrane areas of 7.2 and 25.9 m^2 respectively.

2.7.3.1 Pilot Plant for Studying Combinations of Forward Osmosis and Reverse Osmosis

The plant has three different units (Figure 41) that can be coupled in different ways between them: (i) 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 four vessels that can be connected in series or in parallel, each of which hosting four membranes. The nominal flow rate is 3 m^3/h and the pumping system can work at different pressures up to a maximum of 80 bar. The unit is designed so that SWRO, BWRO or NF membranes can be used. Finally, there is an MF unit with 3 m^3/h nominal flow rate. The installation is completely monitored with pressure sensors, conductivity- and 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.

2.7.3.2 Closed-loop seawater feed system for desalination testing.

The system is composed of three storage tanks connected in series containing a total volume of 300 m^3 of real seawater (Figure 42). The containers are connected to a hydraulic circuit that can supply feed water to the different desalination pilot plants at the required flow rate. The circuit also returns the brine and the distilled water back to the containers, so that the total mass and the salinity are conserved.

Figure 41. Test bed for FO-RO combination research.

Figure 42. Containers filled with real seawater for desalination tests in closed-loop.

2.8 Experimental Solar Treatment of Water facilities

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

- Solar CPC (compound parabolic collector) pilot plants.

- Solar simulators.
- UVC-pilot plant.
- Ozonation pilot plant.
- Nanofiltration pilot plant.
- Pilot plant for photocatalytic production of hydrogen based on solar energy.
- Wet Air oxidation pilot plant.
- Electro-oxidation pilot plant
- Solar UVA monitoring equipment
- Pilot plants for biological treatment.
- Experimental culture camera.

2.8.1 SOLWATER

Solar CPC pilot plants

Since 1994 several CPC pilot plants have been installed at the PSA facilities (Figure 43). Basically, the solar pilot plants are built by modules which can be connected in series. Each module consists of a number of photo-reactors placed on the focus of an anodized aluminium mirror with Compound Parabolic Collector (CPC) shape to optimize solar photons collection in the photo-reactor tube. The modules are placed on a platform titled 37° horizontally to maximize the global solar collection of photons through the year. In addition, the pilot plants are equipped with added systems for different purposes, 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. Summary 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 (20-55°C), flow rate). - 100 L sedimentation tank for catalyst separation
2010 (FIT-2)	4.5	60/45	Flow	50	- -Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), O_2, flow rate) - -Sedimentation tank
2011 (HIDRO-CPC)	2.1	25/14.24	Flow	32	- -Coupled with H_2 generation pilot plant
2011	1	25/11.25	Flow	50	

Year	CPC (m^2)	Total/illuminated volume (L)	Flow or static	Tube diameter (mm)	Added systems/Characteristics
(CPC25)					
2013 (ELECTROX)	2	40/25	Flow	50	- Coupled with electro-photo-Fenton plant
2013 (NOVO75)	2	74/68.2	Flow	75	- Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate)
2013 (CPC25)	1	25/11.25	Flow or static	50	- Variable volume, versatile for different volume of water
2013 (SODIS-CPC)	0.58(x2)	25/25	static	200	- Low cost, no recirculation system
2016 (NOVO 75 V1.0)	2.03 (x2)	34 or 53	Flow or static	75	- Two modules of collectors: CPC versus U-mirror type alternatively used - Tubes installed in vertical position - Air injection in tubes - Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate) - - Automatic control system for filling the system accordingly to incident energy - - Solar panel for water heating

(a)

(b)

Figure 43. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II.

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

A 2 m^2 CPC collector (Figure 44) with 10 borosilicate glass tubes (50 mm diameter), an illuminated volume of 22 L and a total volume of 75 L is connected to four electrocells for experimental research on electro-photo-Fenton processes for decontamination and disinfection of water.

In 2016, a new pilot plant with two modules of 2 m^2-collectors with different mirror shapes (CPC and U mirror type) has been installed at the PSA (Figure 45). 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 by a UVA solar sensor and automatically controlled. In addition, the pilot plant is equipped with a solar water heating panel which allows to increase water temperature prior to filling the photoreactors.

Figure 44. View of 2 m^2-CPC coupled to Electro-Fenton pilot plant (ELECTROX).

Figure 45. 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. Both solar simulators XLS+ contain a UV filter (Suprax) with wavelength limitation of 290 nm simulating external solar radiation. Temperature can also be modified and controlled in both systems by a cooling system (SUNCOOL).

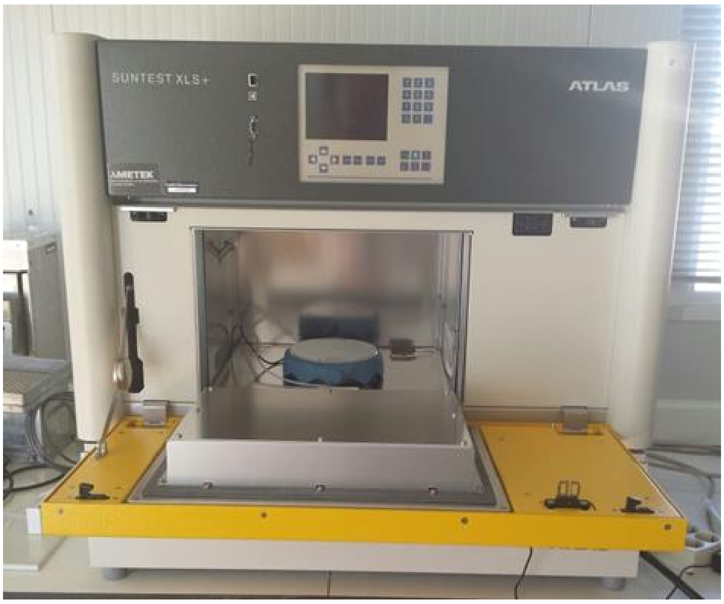


Figure 46. Solar simulator SUNTEST XLS+.

Ozonation pilot plant

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

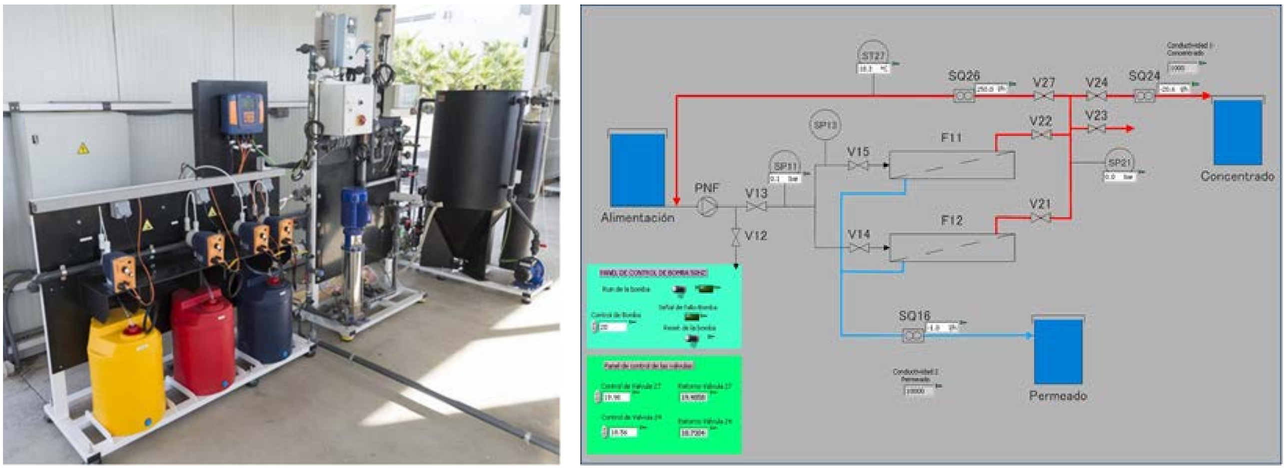
In 2020, the ozonation pilot plant has been improved with the main objective of increasing the gas-liquid mass transfer of the system. The contact column reactor increased its volume from 20 to 580 L (Figure 47.a) and a pressurized system with a total volume of 110 L (Figure 47.b) that allows the sparging of micro or nano-bubbles of ozone (venturi pump, Figure 47.c) has been installed. This ozonation system works in batch mode allowing its combination with other technologies such as, CPC photoreactors (photocatalyst) and the UV-C pilot plant.

(a) (b) (c)

Figure 47. Pictures of the improved parts of the ozonation pilot plant: a) New 580L contact column reactor; b) Pressurized tank; c) Venturi pump for micro or nano-bubbles generation.

Nanofiltration pilot plant

The nanofiltration (NF) system has two working modes, in series and in parallel. The basic system consisted of three FILMTEC NF90-2540 membranes, connected in parallel, with a total surface area of 7.8 m^2. These polyamide thin-film composite membranes work at a maximum temperature of 45°C, a maximum pressure of 41 bar and a maximum flow rate of 1.4 $m^3 \cdot h^{-1}$, whereas operation pH range is 2 - 11. pH control allows the cleanings and evaluating the separation of different compounds in the membranes depending on the pH value. A dosing pump is also included for studying the effect of biocide addition. It has a feeding tank of 400 L (Figure 48.a). In 2016 the nanofiltration system was automatized by including electro-valves and automatic acquisition of the different instrumentation signals (flow, pressure, conductivity, temperature, etc.) with the final aim of stablishing a P&ID control system (Labview interface was implemented, Figure 48.b) for controlling the required quality of the permeate flow generated as well as the concentrated stream.



(a) (b)

Figure 48. a) Nanofiltration pilot plant; b) New labview interface for control and automatic operation of the pilot plant.

UVC pilot plant

The ultraviolet (UV) pilot plant was designed to treat and disinfect water for research and comparison with the solar technologies. This plant consists of three UV-C lamps (max. flow rate 25 $m^3 \cdot h^{-1}$, 254 nm peak wavelength, 400 $J \cdot m^{-2}$ max. power) connected in series, with flexible configurations for a single lamp, two or three lamps in recirculating batch mode or continuous flow mode. Lamps power and flow rate can be regulated according to the needs of the water. Furthermore, the plant is equipped with a dosage system of reactants (acid, base, and hydrogen peroxide). The total volume per batch is 200 - 250 L, with illuminated volume and area of 6.21 L and 0.338 m^2 per lamp module, respectively. The system is equipped with pH and dissolved oxygen sensors in-line and connected to a PROMINENT controller for automatic data acquisition of both parameters (Figure 55).

Wet Air Oxidation pilot plant

A pilot plant was designed and installed in 2016 as a harsh pre-treatment to reduce the complexity of industrial effluents and reaction time of a subsequent solar advanced oxidation process (AOPs) (Figure 49). 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 pressurizing the system, and the use of different metallic salts as catalyst. The Wet Air Oxidation pilot plant consists of a stainless-steel reactor with a total volume of 1 L, a magnetic stirrer, a breakup disk, liquid reagents injector prepared to operate under 200 bar and a maximum temperature of 300°C, thermo-probe, pressure sensor (until 250 bar) and a cooling-heating jacket, all made of stainless steel. The Wet Air Oxidation pilot plant includes an automatic system of control and data acquisition of diverse parameters such as pressure, temperature, reagents dosses and agitation velocity.

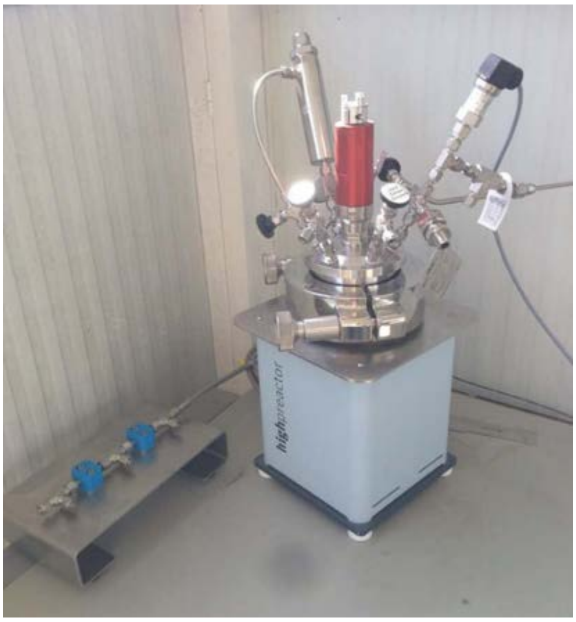


Figure 49. Wet Air Oxidation Pilot plant.

Electro-oxidation pilot plant

Electro-oxidation pilot plant consisted of four undivided commercial electrochemical cells (Electro MP Cell from ElectroCell) conformed by a boron-doped diamond film on a niobium mesh substrate (Nb-BDD) as anode and a carbon-polytetrafluoroethylene (PTFE) gas diffusion electrode (GDE) as cathode, both with 0.010 m^2 effective area single-sides. Electrodes were connected to a Delta Electronika power supply and water from a reservoir is recirculated through the system by centrifugal pumps (Figure 50).

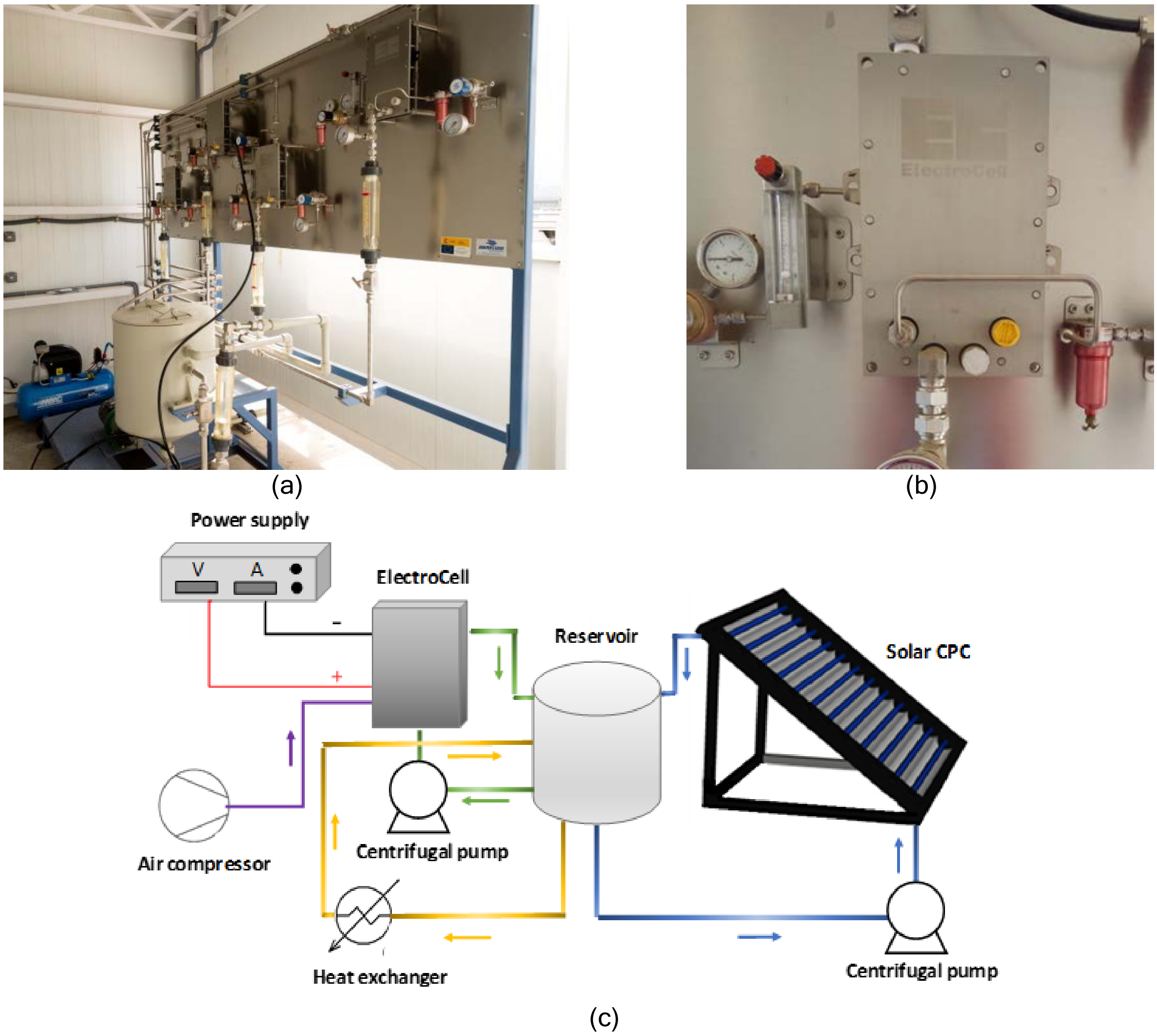


Figure 50. a) Electro-oxidation pilot plant; b) Electrochemical cell of the solar-assisted electrooxidation pilot plant; and c) Schematic diagram of the solar-assisted electrooxidation pilot plant.

Solar UVA monitoring equipment

The UV and global solar radiation data monitoring and storage system is composed by different pyranometers (Figure 51), including global solar radiation in the range of 310-2,800 nm (Kipp and Zonen CMP-6 with sensitivity 5-20 $V \cdot W^{-1} \cdot m^{-2}$, max. value: 2000 $W \cdot m^{-2}$), and global UVA radiation in the range of 300-400 nm (Kipp and Zonen CUV-5 with sensitivity 1 $Mv \cdot W^{-1} \cdot m^{-2}$, max. value: 100 $W \cdot m^{-2}$). Besides this, a spectral photometer with double channel was installed to monitor the solar spectral irradiance at the location of the solar tests. This equipment (AVANTES) has UVA sensors and filters to measure in the whole spectral range of 200 - 1,100 nm.

(a) (b) (c)

Figure 51. CUV-5 pyranometer (a). View of all solar UV pyranometer (horizontal (b) and inclined (c) setup) used in the Solar Treatment of Water Unit).

Biological pilot plant

A biological pilot plant with a double depuration system (Figure 52) consists of a 60 L feeding tank; three Immobilized Biomass Reactors (IBR) of 20-L each one; and two Sequencing Batch Reactors (SBR) of 20-L each one. These modules use the same reception tank (200 L) as well as pH and dissolved oxygen control systems and electronic equipment. In addition, this plant can be operated in continuous or in batch mode. For the batch operation, two conical decantation tanks (40 L) are used. Data acquisition of three MULTIMETERS (M44 CRISON) is available by means of programmable relays and the main parameters are monitored by a SCADA system.

Membrane Distillation (MD)/ Crystallizer pilot plant.

The pilot plant is composed by a MD module integrated into a system consisting of two hydraulically separated loops, one for the hot solution and the other for the cooling solution. A 150 L PP feeding tank provided with a 3 kW_{th} electrical resistance heating system with a feeding pump (Qmax = 1.1 m^3/h, T = 80°C) area available. An internal coil thermostated by a chiller (Qmax = 15.5 L/min, 2,750 W, range = -10 - 40°C) is incorporated in the tank. Refrigeration is controlled by an external temperature sensor and the cooling pump helps to ensure homogeneity by recirculating it into the tank. Two level ultrasound sensors are installed for measuring the permeate volume produced (T = -20 - 60°C, P = 0.7-3 bar). The facility has a PLC to register the variables and as a control to be able to work during 48 H. Moreover, the system is prepared to work with acids and bases, and it has a pH regulation system consisting of a tank (HDPE 50 L), a pump (Qmax = 20 L/h, Pmax = 3 bar, PP), a pH controller and a pH sensor (Range: 0 - 14, Pmax: 3 bar, T = -5 - 70°C). Finally, the system has a 25 L jacketed borosilicate crystallizer with a stirrer inside (range: 0/30 - 1,000 rpm, P: 60 W, material: PTFE) and a pump (flowmeter range: 90 - 900 L/h). The temperature control is carried out by a control system formed by a chiller (Qmax = 15.5 L/min, 2,750 W, range = -10 - 40°C) and an external Pt100 temperature sensor (Figure 53).

Figure 52. Biological pilot plant installed at PSA facilities.

Figure 53. MD + crystallizer pilot plant developed by Apria Systems S.L.

Cultivation chamber

The culture crop chamber of 30 m^2 is used for treated wastewater re-use experience since 2014 (Figure 54). This chamber is made of 10 mm polycarbonate to avoid ultraviolet radiation supported by white rolled steel (Sendzimir). The shoulder height is 2.5 m with a roof slope of 40%. The camera consists of four 3 m^2 x 2.5 m^2 individual areas. Each area is equipped with temperature and humidity sensors, and a cooling and heating system. The crop camera is equipped with a global solar radiometer for measuring the incident solar radiation. So, through this probe an opaque plastic cover located on the top of the camera can be automatically folded and re-folded in order to reduce the incidence of irradiance inside the crop camera. Finally, the roof slope of each area acts as windows which can be automatically opened and closed to favour the airflow inside each area and enhance the efficiency of the temperature control. Sensors registration (temperature, humidity and solar radiation) and temperature control of each individual area (by the cooling and heating system, windows and top plastic cover) is made by using the Ambitrol® software which permits to keep a comfortable temperature for crops of approximately 25°C during the different seasons.

Figure 54. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities.

2.8.2 HYWATOX

Photocatalytic generation of hydrogen pilot plant

The pilot plant for photocatalytic hydrogen generation is composed by a closed stainless-steel tank of 22 L connected to a CPC photo-reactor for the simultaneous removal of organic contaminants from aqueous solutions and hydrogen generation (Figure 56). The tank is fitted with gas and liquid inlet and outlet and a sampling port. Two parallel mass flow controllers are used to control the desired N_2 gas flow into the reactor headspace during the removal of O_2 to achieve the reduction conditions as well as to drag the hydrogen produced. A centrifugal pump (PanWorld NH-100PX) with a flow rate of 20 L·min^{-1} is used to recirculate the aqueous slurry from the tank to the tubes of the CPC. The photo-reactor is composed of 16 Pyrex glass tubes (inner diameter 28.5 mm, outer diameter 32 mm, irradiated length 1,401 mm) mounted on a fixed platform tilted 37° (local latitude). The total area and volume irradiated is 2.10 m^2 and 14.25 L, respectively.

Figure 55. UVC pilot plant installed at PSA facilities.

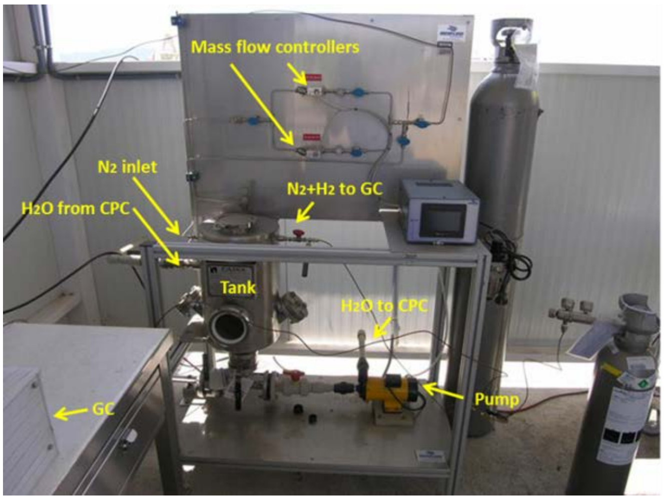


Figure 56. Solar pilot plant for photocatalytic generation of hydrogen.

2.9 Optical characterization and solar reflector durability analysis facility - OPAC

The PSA's optical characterization and solar reflector durability analysis facility, which is the result of a joint collaborative project between CIEMAT and DLR, has the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. This laboratory allows the evaluation of characteristic optical parameters of solar reflectors and their possible deterioration. The following equipment is available in the optical characterization of solar reflectors laboratory (see Figure 57.a):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 15° incidence angle, 660 nm wavelength, and different aperture angles (3.5, 7.5, 12.5 and 23 mrad).
- One portable specular reflectometer, Devices and Services model MWR, for measuring specular reflectance at 15° incidence angle, 460, 550, 650 and 720 nm wavelength, and different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- One portable reflectometer, PSE model pFlex 2.1, for measuring specular reflectance at 8° incidence angle, 470, 525 and 625 nm wavelength, and 67 mrad aperture angle.
- One portable reflectometer, Aragon Photonics model Condor, for measuring specular reflectance at 12° incidence angle, 435, 525, 650, 780, 940 and 1050 nm wavelength and 145 mrad aperture angle.
- One portable reflectometer, Konica Minolta model CM-700d, for measuring hemispherical and diffuse reflectance at 8° incidence angle, and 400-700 nm wavelength.
- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model SR^2, designed and patented by DLR).
- Perkin Elmer Lambda 1050 spectrophotometer, with 150-mm integrating sphere and specular reflectance accessory with 0 to 68° 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 solar reflector durability analysis laboratory is designed for carrying out accelerated ageing tests of these materials with the purpose of predicting in a short time, the behaviour of these materials during their useful lifetime (see Figure 57.b). To do this, the environmental variables producing degradation of solar reflectors when they are exposed to outdoor conditions are applied in a controlled manner, both separately and in combination. The following equipment is available for these accelerated ageing tests:

- Two ATLAS SC340MH weathering chambers for temperature (from -40°C to +120°C), humidity (from 10% to 90%), solar radiation (from 280 to 3000 nm) and rainfall of 340L.
- Vötsch VSC450 salt spray chamber with temperatures from 10°C to 50°C (450 L).
- Erichsen 608/1000L salt spray chamber with temperatures from 10°C to 50°C.
- Two ATLAS UV-Test radiation chambers where UV light (with a peak at 340 nm), condensation and temperature can be applied. One of the chambers also includes rain simulation.
- Hönle UVA Cube Ultraviolet radiation chamber.
- KÖHLER HK300M acid rain chamber, 300 L and temperatures up to 70°C 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 (335 L, see Figure 57.b).
- Ineltec CKEST 300 test chamber for humidity and condensation testing with temperatures up to 70°C (300 L).
- Memmert HCP108 weathering chamber to apply humidity (20-95%) and temperature (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 30 m/s and dust concentrations up to 2.5 g/m³.
- Erichsen 494 cleaning abrasion device to test the degradation due to the cleaning brushes, with several cleaning accessories.
- Taber 5750 linear abraser to check the materials resistance against the abrasion.
- Lumakin A-29 cross-cut tester to analyse the possible detachment of the paint layers.
- Several devices for thermal cycles specially designed at the PSA.
- Spectral Specular Reflectometer S2R for measuring specular reflectance spectra in the wavelength range 280-2500nm at variable incidence angles of 8-70° and discrete acceptance angles of 7.4, 12.3, 14.8, 20.2, 35.9 or 107.4 mrad (designed and patented by DLR).

- Soiling Pipe for simple sand erosion experiments based on DIN 52348. Erodent material hitting the specimen after around 160 cm of free fall under adjustable impact angles (designed by DLR).
- Open loop wind tunnel with particle injection Acetube for the advanced simulation of sand- and dust erosion effects. Wind velocities between 1 and 20 m/s can be set and also fine powders can be used as erodent material (designed by DLR).
- Artificial soiling chamber, equipped with the aerosol generator SAG410/L from TOPAS GmbH and an ultrasonic nebulizer to reach a realistic soiling picture on reflector samples (designed by DLR).

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

(a) (b)

Figure 57. OPAC solar reflector optical characterization lab (a) and durability analysis lab (b)

2.10 Experimental Installations for the Energy Performance Assessment of Buildings and Building Components

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

1) Test cells: The LECE has five test cells, each of them made up of a high-thermal-insulation test room and an auxiliary room. The test room's original south wall can be exchanged for a new wall to be tested. This makes experimental characterisation of any conventional or new building envelope possible.

2) PASLINK Test cell: The Spanish PASLINK test cell incorporates the Pseudo-Adiabatic Shell (PAS) Concept. This system detects heat flux through the test cell envelope by means of a thermopile system and compensates it by a heating foil device. The inner surface of the test room consists of an aluminium sheet which makes it uniform in order to avoid thermal bridging. It also has a removable roof that enables horizontal components to be tested. The cell is installed on a rotating device for testing in different orientations.

3) CETeB Test cell: This is a new test cell for roofs. The design of this test cell solves some practical aspects related to roof testing, such as accessibility and structural resistance. An underground test room that allows easy access to the test component is used for this.

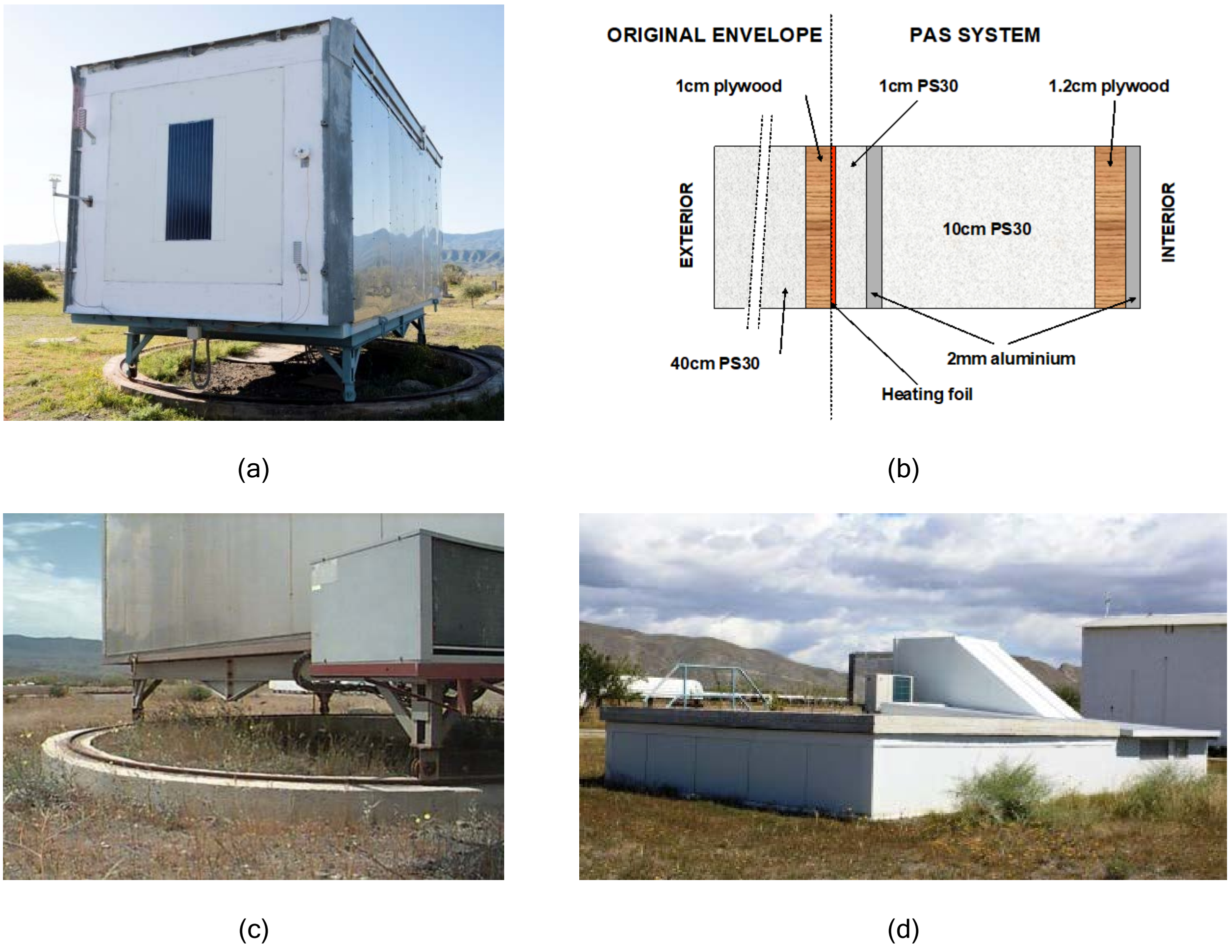


Figure 58. (a) CIEMAT's PASLINK test cell carrying out a thermal test of a PV module, (b) Schematic drawing of the PAS system, (c) Detail of the rotating device, (d) Exterior of the CETeB Test cell.

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) Single-zone building: This is a small 31.83 m^2 x 3.65 m high simple single-zone building built in an area free of other buildings or obstacles around it that could shade it, except for a twin building located 2 m from its east wall. Its simplicity facilitates detailed, exhaustive monitoring and setting specific air conditioning sequences that simplify its analysis for in-depth development and improving energy evaluation methodologies for experimental buildings.

(a) (b)

(c) (d)

Figure 59. (a) Reference single-zone building, (b)ARFRISOL Building Prototype in use, (c) Solar Chimney. Configuration including Phase Change Material tiles, (d) Ventilated façade tested in a Test Cell. Different configurations with light and dark external face.

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 1,000 m2 built area. One of them is at the PSA and the others are in different locations that represent Spanish typical climates. These C-DdIs are designed to minimize energy consumption by heating and air-conditioning, whilst

maintaining optimal comfort levels. They therefore include passive energy saving strategies based on architectural and construction design, have active solar systems that supply most of the energy demand (already low), and finally, have conventional auxiliary systems to supply the very low demand that cannot be supplied with solar energy, using renewable energy resources, such as biomass insofar.

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

3 Laboratories

3.1 Laboratory for the geometrical characterization of solar concentrators - GeoLab

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

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

Photogrammetry consists of a 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).

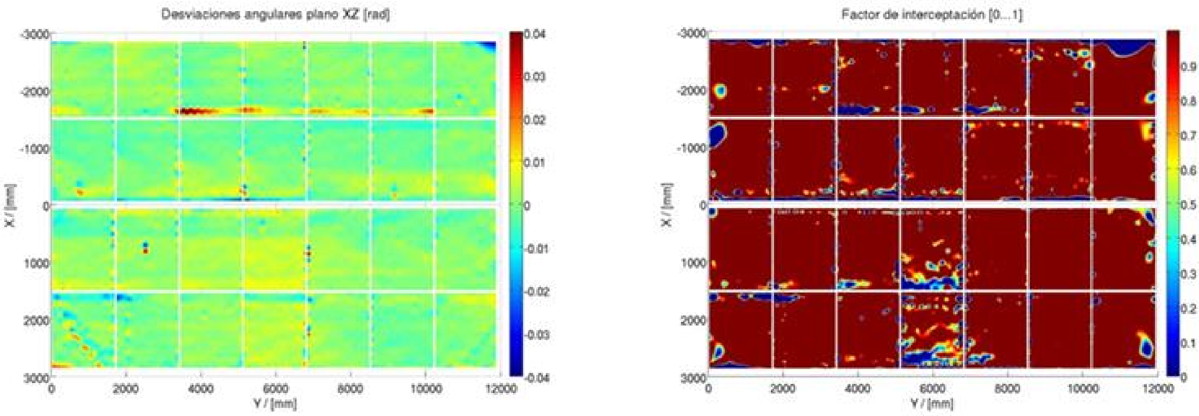
The equipment allocated to this activity at PSA is:

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

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

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

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



(a) (b)

Figure 60. Angular deviations (a) and intercept factor (b) of a parabolic-trough collector module analysed by photogrammetry.

3.2 Radiometry laboratory – RadLab

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

Figure 61. View of the PSA Radiometry equipment.

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

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

- The MIKRON 330 black body is a cylindrical cavity which can provide any temperature from 300°C to 1700°C accurate to ±0.25% and a resolution of 1°C. Its emissivity is 0.99 in a 25-mm-diameter aperture.
- The MIKRON M305 black body is a spherical cavity that can supply any temperature between 100°C and 1000°C accurate to ±0.25% and with a resolution of 1°C. Its emissivity is 0.995 in a 25-mm-dia. aperture.
- The MIKRON M340 black body is a flat cavity and can provide any temperature from 0°C to 150°C accurate to ±0.2°C and a resolution of 0.1°C. Its emissivity is 0.99 in a 51-mm-aperture.

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

Figure 62. IR sensor calibration using a black body.

3.3 Receivers testing and characterization for concentrating solar thermal systems - SRTLab

This activity line comprises both linear tube-type receivers and volumetric air receivers. The equipment associated to linear receivers is located at PSA and the two main test devices are: a) a test bench called HEATREC (see Figure 63.a), for measuring heat loss of single receiver tubes under indoor laboratory conditions, and b) an outdoor test bench called RESOL (see Figure 63.b), 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.

(a)

(b)

Figure 63. View of the HEATREC test chamber to measure heat losses in solar receiver tubes (a) and RESOL test bench to measure receiver's optical efficiency (b).

The 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 an energy balance of the system. The test provides in one measurement the receiver optical efficiency, i.e., the combined value of the absorptance and transmittance of the receiver tube.

HEATREC device allows characterizing 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 4,060 mm-long and with absorber tube diameter of 70 mm.

Besides HEATREC and RESOL, the activity line dedicated to linear receivers is equipped with tools and devices for proper manipulation and monitoring of receiver tubes.

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

The activity line 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 solar central receivers, thus requiring an accelerated ageing to study the durability of the most critical components of solar thermal power plants, not only absorber materials, but also surface treatments and coatings that increase their absorptance. It is therefore necessary to find out and study the mechanisms of the physical degradation and breakage of these materials at high temperatures under concentrated solar radiation.

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

- The Metallography Room
- The Microscopy Room
- The Thermogravimetry Room
- The Thermal Cycling Room
- The Scanning Electronic Microscope Room

The laboratory equipment located in these rooms is listed below.

3.4.1 Metallography Room

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

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

Figure 64. View of the Metallography Room in the Solar Furnaces building

3.4.2 Microscopy Room

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

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

3.4.3 Thermogravimetry Room

The thermogravimetric Balance SETSYS Evolution18 is a TGA, DTA, DSC balance (temperature range from ambient to 1,750°C) whose equipment has been improved including a compact recirculating cooler (Julabo FC1600T) and a thermostatic line to 200°C, with a security box for tests in presence of H_2. It has been adapted for its simultaneous connection to a controlled evaporator mixer and a microGC. Its design allows tests under any gas atmosphere and up to 1,750°C, including:

- Tests under pure Hydrogen atmosphere up to 1,750°C
- Tests under pure Oxygen atmosphere
- Tests under H2O steam with other gases simultaneously.
- Tests under corrosive atmosphere up to 1,000°C

(a) (b)

Figure 65. View of a) the Microscopy Room, and b) the thermogravimetric balance inside of its Room.

This room is also equipped with:

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

3.4.4 Thermal Cycling Room

It includes the instrumentation necessary for thermal cycling:

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

3.4.5 Electronic microscope Room

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

3.5 PSA Water Technologies Laboratory - WATLAB

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

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

3.5.1 General laboratory

The main laboratory is 94 m^2 (Figure 66). 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 fluorometer, a vacuum distillation system, ultrapure water system, pH gauge, turbidimeter 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 suspended and supported activated sludge respirometry (BMT) toxicity and biodegradability measurement devices and required equipment for the analysis of biological oxygen demand (BOD), toxicity and phytotoxicity tests (acute and chronic) and chemical oxygen demand (COD). In addition, a Jar-Test system is also available for the optimization of physicochemical separation studies.

Figure 66. General view of the new PSA Water Technologies Lab.

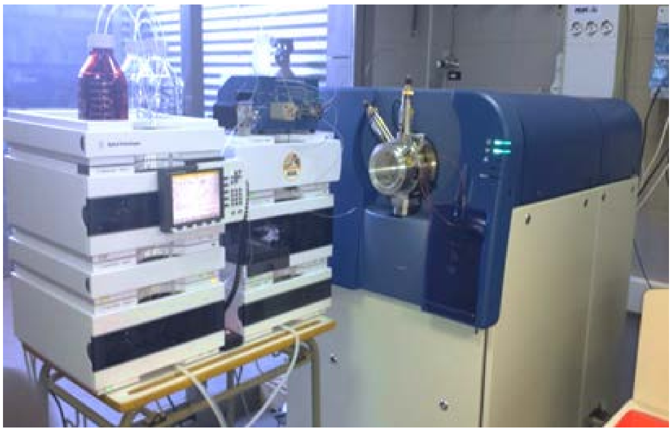
3.5.2 Chromatography laboratory

This laboratory (Figure 67.b) is equipped with three high performance liquid chromatographs with diode array detector (HPLC-DAD and two UPLC-DAD) with quaternary pumps and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which allows working with a low concentration of pollutants (Figure 67.c) and two ion chromatographs (Figure 67.a): one configured for isocratic analysis of amines and cations (Metrohm 850 Professional IC), and another for gradient analysis of anions and carboxylic acids (Metrohm 872 Extension Module 1 and 2) with conductivity detectors (Methrom 850 Professional IC detector). Two total organic carbon (TOC) analysers by catalytic combustion at 670°C and total nitrogen (TN) analyser with autosampler are also available. In addition, an AB SCIEX TripleTOF 5600+ was acquired to detect and identify non-targeted or unknown contaminants present in wastewater or generated (transformation products) during the water treatments: Triple TOF by a DuoSpray Source combining Turbo Ion Spray and APCI (Atmospheric Pressure Chemical Ionization) modes. Besides, the system includes a metabolomics statistical package to analyse multiple samples from multiple experiments and identify possible chemical and biological markers (Figure 67.d).

(a)

(b)

(c)



(d)

Figure 67. a) Metrohm Ion chromatograph System. b) General view of the chromatography lab at PSA facilities. c) Agilent Ultra-fast UPLC-DAD analyzer. d) SCIEX TripleTOF 5600+ equipment.

3.5.3 Microbiology laboratory

47-m^2 microbiology laboratory with biosafety level 2 (Figure 68) is equipped with five microbiological laminar flow (class-II) cabins, two autoclaves, three incubators, a fluorescence and phase contrast combination optical microscope with a digital camera incorporated. Besides this, an automatic grow media preparer, a plaque filler and a filtration ramp with six 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. A homogenizer stomacher 400 Comecta equipment was acquired to blend food samples, stir and store in a reproducible way without any risk of cross contamination between samples.

Figure 68. General view of the microbiology lab at PSA facilities

3.5.4 Microscopy laboratory

The microscopy laboratory is an 11 m^2 room (Figure 69.a) in which a Scanning Electron Microscope (SEM) is installed. Besides, the microscopy laboratory also has an environmental secondary electron detector (ESED). For the preparation of microbiological samples and catalysts to be analysed in the SEM, the system is complemented with a metal coater and critical point dryer. In this room there are also two optical microscopes: i) a fluorescence and phase contrast combination optical microscope and, ii) a FISH microscope (Leyca) with fluorescence module to develop the FISH (Fluorescent in situ hybridation) technique for visualization of DNA hibrydation with specific probes in live cells used for monitoring of key microorganisms within a heterogeneous population (Figure 69.b).

(a) (b)

Figure 69. a) SEM (Scanning Electron Microscope). b) Optical microscope for FISH technique.

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.

3.6 Laboratory for the Assessment of Thermal Storage Materials - TESLab

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

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

Additionally, a device for measuring thermal conductivity of solids is available.

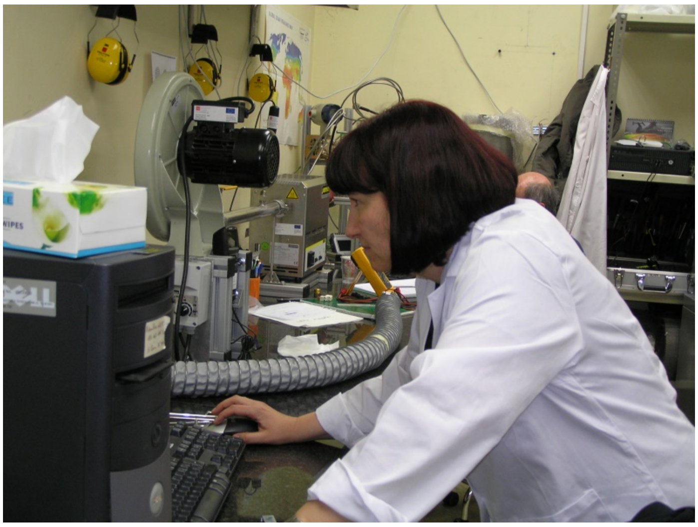


Figure 70. Working using the HDR device

3.7 PSA Desalination Laboratory

3.7.1 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 (Figure 71) 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 an 80 litres tank equipped with an electric heater (3 kW) controlled by a thermostat (90°C maximum), and circulation is made from the storage and the feed side of the module by a centrifugal pump. On the cold side, there is a chiller (800 W at 20°C) controlled by temperature and water is circulated between a cold storage of 80 litres and the module. The circuit is heat insulated and fully monitored for temperature, flow rate and pressure sensors, connected to a SCADA system.

Figure 71. Bench-scale unit for testing membranes on isobaric MD.

3.7.2 Bench-Scale Unit for Flat Sheet Membrane Distillation Testing

The facility is a high precision laboratory (Figure 72) designed for testing fundamental and feasibility test trials on membrane distillation. It possesses the following unique features that are essential for representative and scalable results:

1) Cell format with representative flow distribution. The 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 0.05°C.

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

3.7.3 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 (Figure 73). There is, therefore, one pump for the draw solution and two for the feed solution, each with variable flow and flow-rate measurements. The hydraulic circuit has been modified so that the modules can be operated in pressure-retarded osmosis (PRO) mode. For that purpose, steel pipes and a high-pressure pump (3 L/min; up to 17 bar) are installed in the draw side, and cells with operational pressure up to 15 bar are used. Each cell has a total effective membrane area of 100 cm^2, and hydraulic channels in zigzag 4 mm wide and 2 mm deep. The system uses one container for the draw solution and two for the feed solutions, each placed on a balance in order to measure changes in the mass flow rates of the draw solution and the feed solution of each cell. The containers have an automatic dosing system to keep the salinities constant. The system has two conductivity meters for low salinity and one for high salinity, as well as pressure gauges in each line and temperature readings.

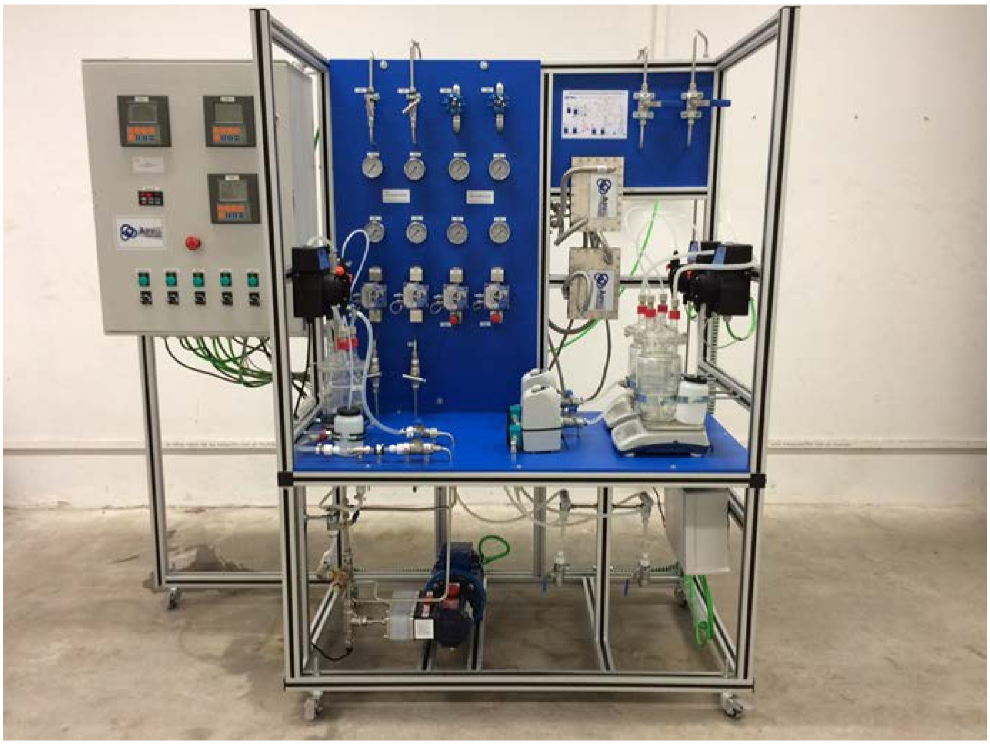


Figure 73. Bench-scale unit for testing FO and PRO.

3.8 Advanced Optical Coatings Laboratory - OCTLAB

This laboratory line is dedicated to the development and complete study of new selective coatings for absorbent materials used in solar concentrating systems at medium and high temperature (up to 700°C), as well as of anti-reflective treatments for glass covers used in some high temperature receiver designs, such as receiver tubes in parabolic-trough collectors. The equipment dedicated 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 also be used for optical characterization of solar reflectors, thus complementing that specifically dedicated to the activity line focussed on testing and characterizing solar reflectors.

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

- Perkin Elmer LAMBDA 950 UV-VIS-NIR Spectrophotometer equipped with a 150mm Spectralon coated integrating sphere. (Figure 74.a).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrating sphere manufactured by Pike (Figure 74.b)
- *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. For measuring emissivity, it has a semi-cylindrical tunnel which emits infrared radiation at 70°C.
- LEICA DM4 M optical microscopy with image acquisition system and software for image analysis (Figure 74.c).
- KSV CAM200 goniometer for measuring contact angles (Figure 74.d).

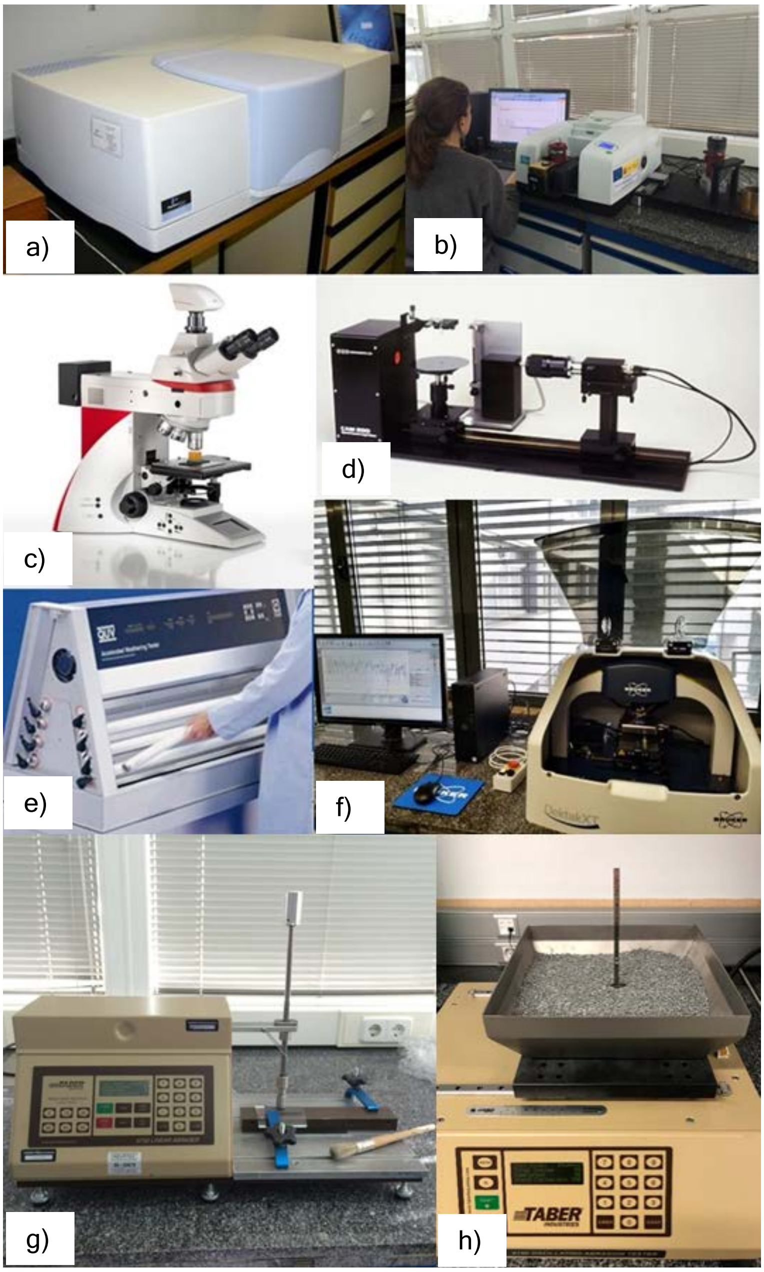


Figure 74. Advanced optical coatings laboratories equipment.

- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (Figure 74.e).
- BROOKFIELD LVDV-I+ Viscometer.
- BRUKER DektakXT stylus profilometer with optical camera and software for surface analysis (Figure 74.f).
- TABER linear abrader model 5750, equipped with different types of abrasive materials to measure the abrasion resistance of coatings and materials (Figure 74.g).
- TABER oscillating abrasion tester, Model 6160, to measure the relative abrasion resistance of the materials to surface abrasion and / or marring produced by sand movement. Different types of standardized sands are available (Figure 74.h).
- Kilns. There are three kilns for thermal treatment:
  - 120x100x300 mm kiln with a maximal temperature of 1,200°C.
  - Controlled atmosphere kiln with a maximal temperature of 800°C.

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

3.9 Porous media laboratory for solar concentrating systems - POMELAB

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

1) Thermal characterization of volumetric absorbers.

Its main component is a test bench designed for the thermal test of new volumetric absorbers and configurations and it's ageing in steady and dynamic conditions. The main components installed in this test bench (Figure 75) are:

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

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

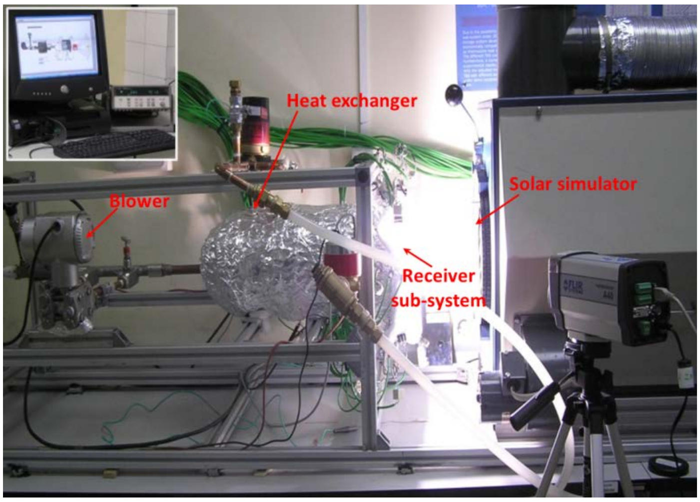


Figure 75. Test bench for volumetric receiver testing.

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

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

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

- Sodeca Blower with velocity control
- Hastinik ball valve of 1 ½".
- Airflow anemometer
- Nabertherm heating resistor
- Honeywell pressure difference-meter

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

Figure 76. Test bench for pressure difference measurement with configuration up to 300°C.

3.10 Solar Fuels Laboratory - SFUELS

The laboratory located in CIEMAT-Moncloa (Madrid) is equipped with the necessary instrumentation for characterization of materials for thermochemical cycles. The loop consists of a 1,600°C high temperature furnace suitable for a variety of applications; coupled to a gas chromatograph (Varian CP4900) equipped with a molecular sieve column and a TCD detector, etc. Finally, a muffle furnace is available for the cycling of materials providing temperatures of around 1,700°C with precise temperature control.

3.11 PSA radiometric net

The PSA has had a meteorological station since 1988, primarily for measuring broadband surface solar radiation (global, direct and diffuse radiation), but also for other generic meteorological variables (temperature, wind speed and direction, relative humidity and atmospheric pressure, accumulated precipitation, etc.). The old station was completely remodelled in 2005 following the strictest requirements of quality and precision in the measurement of solar radiation according to the Baseline Surface Radiation Network guidelines. This station is called METAS station since 2012 (Figure 77).

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

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

Figure 77. General view of METAS station.

Additionally, a set of complementary structures for the calibration of radiometers has been installed near to this meteorological station following the standardized international procedures (ISO-9059 and ISO-9846). On the one hand, a high-performance tracker with the possibility of carrying 2 reference pyreheliometers (absolute cavity radiometer PMOD PMO6-CC) and a total of 19 field pyreheliometers have been installed close to METAS. On the other hand, 3 calibration benches with capacity to carry 20 pyranometers each one, which have been placed at 50 meters of METAS (Figure 78). These facilities are operated in collaboration with the Instrumentation Unit.

Figure 78. Calibration facilities.

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

Figure 79. PSA radiometric stations.

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