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Table of contents

1 General Presentation ... 1

2 Facilities and Infrastructure ... 5

2.1 Parabolic Trough Systems ... 5

2.1.1 The DISS experimental plant ... 5

2.1.2 The HTF Test Loop ... 7

2.1.3 The Parabolic Trough Test Loop (PTTL) facility ... 8

2.1.4 PROMETEO: Test facility for checking new components and heat transfer fluids for large-parabolic troughs ... 9

2.1.5 TCP-100 2.3-MWth parabolic-trough facility ... 10

2.1.6 Innovative Fluids Test Loop (pressurized gases) in parabolic-trough collectors ... 10

2.2 Installations associated with Parabolic Trough Systems ... 12

2.2.1 KONTAS: Rotary test bench for parabolic trough systems ... 12

2.2.2 Accelerated full lifecycle tests of rotation and expansion performing assemblies (REPAs) for parabolic troughs systems ... 13

2.3 Central Receiver Systems ... 14

2.3.1 The 6 MWth CESA-1 Plant ... 14

2.3.2 The SSPS-CRS 2.5 MWth facility ... 16

2.3.3 AORA Solar Tower facility ... 17

2.4 Parabolic DISH Systems ... 18

2.4.1 Accelerated ageing test bed and materials durability ... 18

2.4.2. EURODISH ... 19

2.5 Installation of Solar Furnaces ... 19

2.5.1 SF-60 Solar Furnace ... 19

2.5.2 SF-40 Solar Furnace ... 21

2.5.3 SF-5 Solar Furnace ... 22

2.6 Thermal Storage Systems ... 23

2.6.1 Molten Salt Test Loop for Thermal Energy Systems ... 23

2.7 Experimental Solar Desalination Installations ... 24

2.7.1 Multi-Effect Distillation Facilities ... 24

2.7.2 CSP+D test facilities ... 27

2.7.3 Membrane Desalination Test Facilities ... 29

2.8 Experimental Solar Detoxification and Disinfection Installations ... 33

2.8.1 Solar CPC pilot plants ... 33

2.8.2 Solar simulators ... 36

2.8.3 Ozonation pilot plant ... 36

2.8.4 Nanofiltration pilot plant ... 37

2.8.5 UVC-H_2O_2 pilot plant....37
2.8.6 Photocatalytic generation of hydrogen pilot plant....38
2.8.7 Wet Air Oxidation pilot plant....39
2.8.8 Electro-oxidation pilot plant....39
2.8.9 Solar UVA monitoring equipment....39
2.8.10 Biological pilot plant....41
2.8.11 Cultivation chamber....41
2.9 Experimental Installations for the Evaluation of the Energy Efficiency in Buildings....42
3 Laboratories....45
3.1 Laboratory for the geometrical characterization of solar concentrators - GeoLab....45
3.2 Solar reflector durability analysis and optical characterization labs....46
3.3 Radiometry laboratory – RadLab....48
3.4 Laboratory for the assessment of the durability and characterization of materials under concentrated solar radiation - MaterLab....49
3.4.1 Metallography Room....50
3.4.2 Microscopy Room....50
3.4.3 Thermogravimetry Room....51
3.4.4 Thermal Cycling Room....51
3.5 Receivers testing and characterization for concentrating solar thermal systems - SRTLab....52
3.6 Advanced Optical Coatings Laboratory - OCTLAB....53
3.7 Porous media laboratory for solar concentrating systems - POMELAB....54
3.8 Laboratory for testing instrumentation and equipment for molten salt loops (BES-I and BES-II)....57
3.9 Laboratory for the Assessment of Thermal Storage Materials....57
3.10 Atmospheric Air Packed Bed Test Bench (ALTAYR)....59
3.11 PSA Water Technologies Laboratory - WATLAB....59
3.11.1 General laboratory....60
3.11.2 Chromatography laboratory....60
3.11.3 Microbiology laboratory....61
3.11.4 Microscopy laboratory....62
4 Solar Concentrating Systems Unit....63
4.1 Introduction....63
4.2 Projects....63
4.3 Medium Concentration Group....67
4.3.1 Introduction....67
4.3.2 Projects....68
4.4 High Concentration Group....75
4.4.1 Introduction....75

4.4.2 Projects 76
5 Thermal Storage and Solar Fuels Unit 80
5.1 Introduction 80
5.2 Projects 81
6 Solar Desalination Unit 90
6.1 Introduction 90
6.2 Projects 91
7 Solar Treatment of Water Unit 97
7.1 Introduction 97
7.2 Projects 98
8 Horizontal R&D and Innovation activities 109
8.1 Solar Facilities for the European Research Area - Third Phase, SFERA-III 109
8.2 Integrating National Research Agendas on Solar Heat for Industrial Processes, INSHIP 110
8.3 Implementation of the Initiative for Global Leadership in Solar Thermal Electricity, HORIZON-STE 112
9 Training and educational activities 114
10 Events 116
11 Publications 123
PhD Thesis 123
Solar Concentrating Systems Unit 123
Thermal Storage and Solar Fuels Unit 127
Solar Desalination Unit 128
Solar Treatment of Water Unit 130
Energy Efficiency in Building R&D Unit 137

List of figures

Figure 1. Integration of the PSA in the CIEMAT organization. 1
Figure 2. Aerial view of the PSA. 2
Figure 3. Internal organizational structure of PSA in 2019. 2
Figure 4. Distribution of permanent personnel at the PSA as of December 2019. 3
Figure 5. PSA staff in 2019. 4
Figure 6. Simplified flow diagram of the PSA DISS loop. 5
Figure 7. View of the DISS plant solar field in operation. 6
Figure 8. Diagram of the HTF test Loop located at the PSA. 7
Figure 9. Simplified scheme of the PTTL facility 9
Figure 10. View of the PROMETEO test facility. 10
Figure 11. Diagram of the TCP-100 2.3 MWth parabolic-trough facility 11
Figure 12. View of the IFL experimental facility (with parabolic troughs) using compressed gas as heat transfer fluid. 11
Figure 13. Simplified system diagram of the IFL experimental facility located at the PSA. 12
Figure 14. Side view of KONTAS test bench and the heating cooling unit. 13
Figure 15. Schematic diagram of the REPA test loop at PSA (a) and north view of the test facility (b). 14
Figure 16. The CESA-I facility seen from the north. 15
Figure 17. On-line measurement of the solar extinction in the control room of CESA-1 facility at PSA. 16
Figure 18. Aerial view of the experimental SSPS-CRS facility. 16
Figure 19. An autonomous heliostat in the SSPS-CRS field. 17
Figure 20. General view of the AORA solar tower facility. 18
Figure 21. View of a parabolic-dish DISTAL-I used for accelerated materials ageing at PSA. 19
Figure 22. View of a parabolic-dish DISTAL-II. 19
Figure 23. Front and back views of the EURODISH. 20
Figure 24. HT120 heliostat with new PSA facets. 20
Figure 25. Back side of facet. 20
Figure 26. HT120 heliostat in tracking. 21
Figure 27. Interior view of the PSA SF-60 Solar Furnace in operation. 21
Figure 28. Interior of the SF-40 solar furnace, showing the parabolic concentrator. 22
Figure 29. Concentrator of the SF-5 Furnace. 23
Figure 30. Molten Salt (MOSA) Test Loop for Thermal Energy Systems. 24
Figure 31. 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). 25
Figure 32. The 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II). 26
Figure 33. View of the outside of the CSP+D test bed building with the air coolers (a) and partial view of the interior of the CSP+D test bench (b). 27

Figure 34. NEP PolyTrough 1200 solar field. 28
Figure 35. 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). 29
Figure 36. Internal (a) and external (b) views of the Membrane Distillation experimental test bed within the PSA low-temperature solar thermal desalination facility. 30
Figure 37. Bench-scale unit for testing membranes on isobaric MD. 31
Figure 38. Bench-scale unit for testing MD with flat-sheet membranes. 31
Figure 39. Bench-scale unit for testing FO and PRO. 32
Figure 40. Test bed for FO-RO combination research. 33
Figure 41. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II. 35
Figure 42. View of 2 m^2-CPC coupled to Electro-Fenton pilot plant (ELECTROX). 36
Figure 43. View of new CPC and U-type photoreactors (NOVA 75 V 1.0). 36
Figure 44. Solar simulator SUNTEST XLS+. 36
Figure 45. a) Equipment for humidity elimination in ozone gas outlet; b) Thermo-catalytic ozone destructor; (c) Dissolved ozone sensor. 37
Figure 46. a) Nanofiltration pilot plant photo; b) New lavbiew interface for control and automatic operation of the pilot plant. 38
Figure 47. UVC pilot plant installed at PSA facilities. 38
Figure 48. Solar pilot plant for photocatalytic generation of hydrogen. 38
Figure 49. Wet Air Oxidation Pilot plant. 39
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. 40
Figure 51. CUV-5 radiometer (a). View of all solar UV radiometers (horizontal (b) and inclined (c) setup) used in the Solar Water Treatment Unit). 40
Figure 52. Biological pilot plant installed at PSA facilities. 41
Figure 53. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities 42
Figure 54. (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. 43
Figure 55. (a) Solar Chimney. Configuration including Phase Change Material tiles, (b) Reference single-zone building, (c) ARFRISOL Building Prototype in use. 44
Figure 56. Angular deviations (a) and intercept factor (b) of a parabolic-trough collector module analysed by photogrammetry. 46
Figure 57. OPAC solar reflector optical characterization lab (a) and durability analysis lab (b) 47
Figure 58. View of the PSA Radiometry equipment. 48
Figure 59. IR sensor calibration using a black body. 49
Figure 60. View of the Metallography Room in the Solar Furnaces building 50
Figure 61. View of a) the Microscopy Room, and b) the thermogravimetric balance inside of its Room. 51

Figure 62. 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). 52
Figure 63. Advanced optical coatings laboratories equipment. 54
Figure 64. Test bench for volumetric receiver testing. 55
Figure 65. Test bench for porous material characterization. Static configuration (a), dynamic configuration (b). 56
Figure 66. Test bench for pressure difference measurement with configuration up to 300°C. . 57
Figure 67. Adjusting pressure at BES-II. 58
Figure 68. Working using the HDR device 58
Figure 69. Picture taken from the uppest part of the tank, showing its internal room and thermocouples at different lengths and radial positions. 59
Figure 70. Researcher adjusting some items from the upper top of the tank. 59
Figure 71. General view of the new PSA Water Technologies Lab. 60
Figure 72. 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. 61
Figure 73. General view of the microbiology lab at PSA facilities. 61
Figure 74. a) SEM (Scanning Electron Microscope). b) Optical microscope for FISH technique 62
Figure 75. Test bench exposed outdoor at the PSA (a) and real operating test for secondary mirrors at the PSA solar furnace (b). 64
Figure 76. Simplified skecth of an innovative linear Fresnel solar collector (iLFC) developed in the SOLTERMIN project (a) and first prototype of iLFC under construction during a flux measurement test (b). 66
Figure 77. Medium Concentration Group staff working a) at PSA in Tabernas (Almería) and b) at CIEMAT Headquarters in Madrid. 68
Figure 78. Artificial dust barrier by Cranfield University (a) and ultrasonic cleaning system by IK4-Tekniker (b) 69
Figure 79. SIMON project: Experimental data during continuous operation of PROMETEO test facility with HELISOL® XA at 425°C. 71
Figure 80. Daily thermal energy delivered by a PTC solar field to a pasteurization process (with 3h TES or with no TES), as percentage of the total demand, using meteorological data of PSA, Spain. 73
Figure 81. High Concentration Group Staff working at the PSA (a) and CIEMAT-Madrid (b). . 75
Figure 82. Erection of the testing equipment of the CAPTURE project in the CRS solar tower facility at PSA (left) and first commissioning tests (left). 77
Figure 83. New absorber configurations tested at solar simulator (a) and testing facility for accelerated aging of the absorber samples (b). 78
Figure 84. Weather station at the *Plataforma Solar del Desierto de Atacama* (PSDA) in Antofagasta (Chile). It is equipped with a large variety of instruments ranging from atmospheric parameter measurements to solar resource measurements. 79
Figure 85. Staff of ATYCOS working on Thermal Storage Group line in 2019 80
Figure 86. Staff of the Solar Fuels Group. 81

Figure 87. Thermal gauges assignment and location within the storage tank of Polyphem TSS. ... 82
Figure 88. Measured temperature along ALTAYR tank length in a charge process. ... 83
Figure 89. Photograph of the final configuration. ... 85
Figure 90. Sample under solar exposure at the SF40 facility. ... 87
Figure 91. CAD model of the lunar test reactor. ... 88
Figure 92. New filter for the Oresol plant ... 89
Figure 93. Members of the UDeS Unit. ... 90
Figure 94. Pilot-plant for assessment of combined reverse electrodialysis and membrane distillation. ... 92
Figure 95. Results of SEC (a) and SWC (b) *vs* condensation power (CP) in the different hybrid cooler configurations. Level 3 corresponds to a condensation power between 120-125 kW_{th}, Level 4 corresponds to a condensation power between 170-175 kW_{th} and Level 5 corresponds to a condensation power between 200-225 kW_{th} (nominal conditions) ... 95
Figure 96. a) Solar CPC reactor prototype of 25 L under natural sunlight at PSA facilities. b) Inactivation kinetics constant of all pathogens tested with 5 mg/L-H_2O_2/Solar and 5 mg/L-H_2O_2/Solar/O_2 ... 99
Figure 97. a) Laboratory scale set-up for photo-electrocatalysis (PEC) experiments at Ulster University facilities. b) Inactivation profile of *E. coli* by carbon felt-PEC treatment alone and in the presence of holes´acceptors. ... 100
Figure 98. (a) New photocatalytic-UF membranes carried out in Liqutech within the AQUALITY project. (b) Schematic overview of the experimental set-up using a 250 ml beaker for testing new photocatalytic ceramic membranes (40x40) placed on the bottom. ... 102
Figure 99. (a) Effect of new photocatalysts on the inactivation of E. Coli in simulated effluent of a municipal wastewater treatment plant. (b) Simultaneous elimination of Sulfametoxathole (SMX) in the same water matrix and with the same new developed photocatalysts (same legend as in (a)). ... 102
Figure 100. PCED reactor prototype constructed by University of Istanbul. ... 103
Figure 101. UV-Vis-NIR Diffuse reflectance spectra of the studied catalysts. ... 104
Figure 102. Simultaneous bacterial inactivation and MCs degradation (inset) under UVC radiation in simulated secondary effluent of a municipal wastewater treatment plant as a function of treatment time. Dashed lines refer to detection limit (DL = 1 CFU 100 mL-1) and 80% removal of total MCs. ... 106
Figure 103. a) Different ZVI sources: (i) commercial steel wool (ZVI-SW), (ii) ZVI microspheres (ZVI-MS) and (iii) ZVI powder (ZVI-S). b): Imidacloprid degradation profiles by solar ZVI technology at neutral pH. ... 107
Figure 104. AQUACYCLE dissemination poster. ... 108
Figure 105. Photo of the participants in the kick-off meeting held at the PSA. ... 110
Figure 106. INSHIP Management Board Meeting (Freiburg, Germany, 8th May 2019). ... 111
Figure 107. HORIZON-STE Kick-off Meeting (Brussels, Belgium, 7th May 2019). ... 113

List of tables

Table 1. Summarize of CPC pilot plants at PSA facilities. 34

1 General Presentation

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

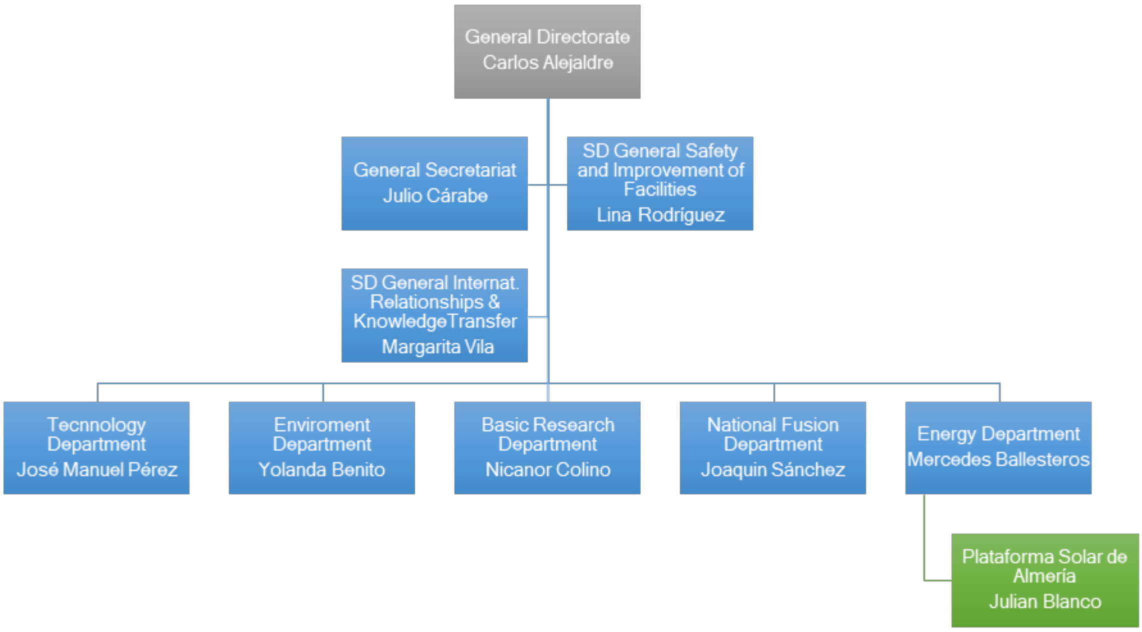


Figure 1. Integration of the PSA in the CIEMAT organization.

The following goals inspire its research activities:

- Contribute to establishing a sustainable clean world energy supply.
- Contribute to the conservation of European energy resources and protection of its climate and environment.
- Promote the market introduction of solar thermal technologies and those derived from solar chemical processes.
- Contribute to the development of a competitive Spanish solar thermal export industry.
- Reinforce cooperation between business and scientific institutions in the field of research, development, demonstration, and marketing of solar thermal technologies.
- Strengthen cost-reducing techno-logical 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.

Figure 2. Aerial view of the PSA.

Since 2018, research activity at the Plataforma Solar de Almería has been structured around four R&D Units under a Technical Coordinator, plus a strong unit that manages and also coordinates all facilities and laboratories, known as 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.

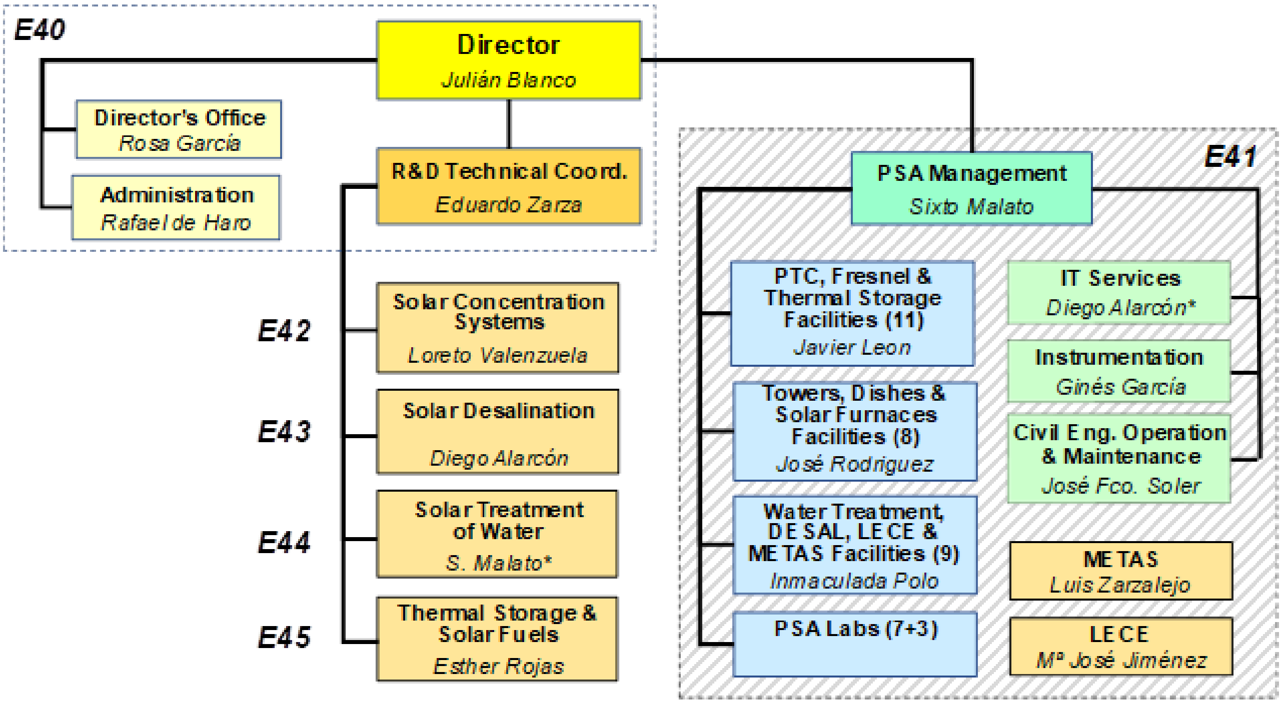


Figure 3. Internal organizational structure of PSA in 2019.

The four R&D Units are as follows:

- Solar Concentrating Systems. This unit develops and studies components for solar fields, complete systems, and applications of concentrated solar thermal energy technologies, for electricity generation and industrial process heat.
- Solar Desalination. Its objective is to develop brackish water and seawater solar desalination.
- Solar Water Treatment. Exploring the chemical possibilities of solar energy, especially its potential for water detoxification and disinfection.
- Thermal Storage & Solar Fuels. The objective of this Unit is providing solutions to concentrating solar thermal systems to become a dispatchable technology, by thermal storage systems and/or Hydrogen production by thermochemical 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 four R&D units share many PSA resources, services, and infrastructures, so they stay in fluid communication with the Direction and Services Units, which coordinate technical and administrative support services. For its part, the Director's Office must ensure that the supporting capacities, infrastructures, and human resources are efficiently distributed. It is also the Director's Office that channels demands to the different general support units located at CIEMAT's main offices in Madrid.

The PSA's scientific and technical commitments and the workload this involves are undertaken by a team of 135 persons that as of December 2019 make up the permanent staff providing their services to the PSA. In addition to this staff, there is a significant flow of personnel in the form of visiting researchers, fellowships and grants handled by the Director's Office. Out of the 121 people who work daily for the PSA, 62 are CIEMAT personnel, 11 of whom are located in the main offices in Madrid.

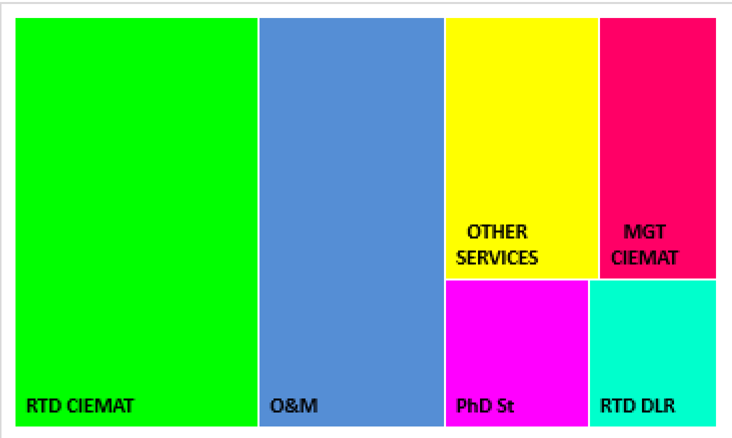


Figure 4. Distribution of permanent personnel at the PSA as of December 2019.

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

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

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

The PSA operating budget in 2019 totals 3.7 M€ (not including R&D personnel or new infrastructure).

Figure 5. PSA staff in 2019.

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 400°C as it circulates through the absorber tubes of a 700-m-long row of parabolic-trough collectors with a total solar collecting surface of 3,838 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).

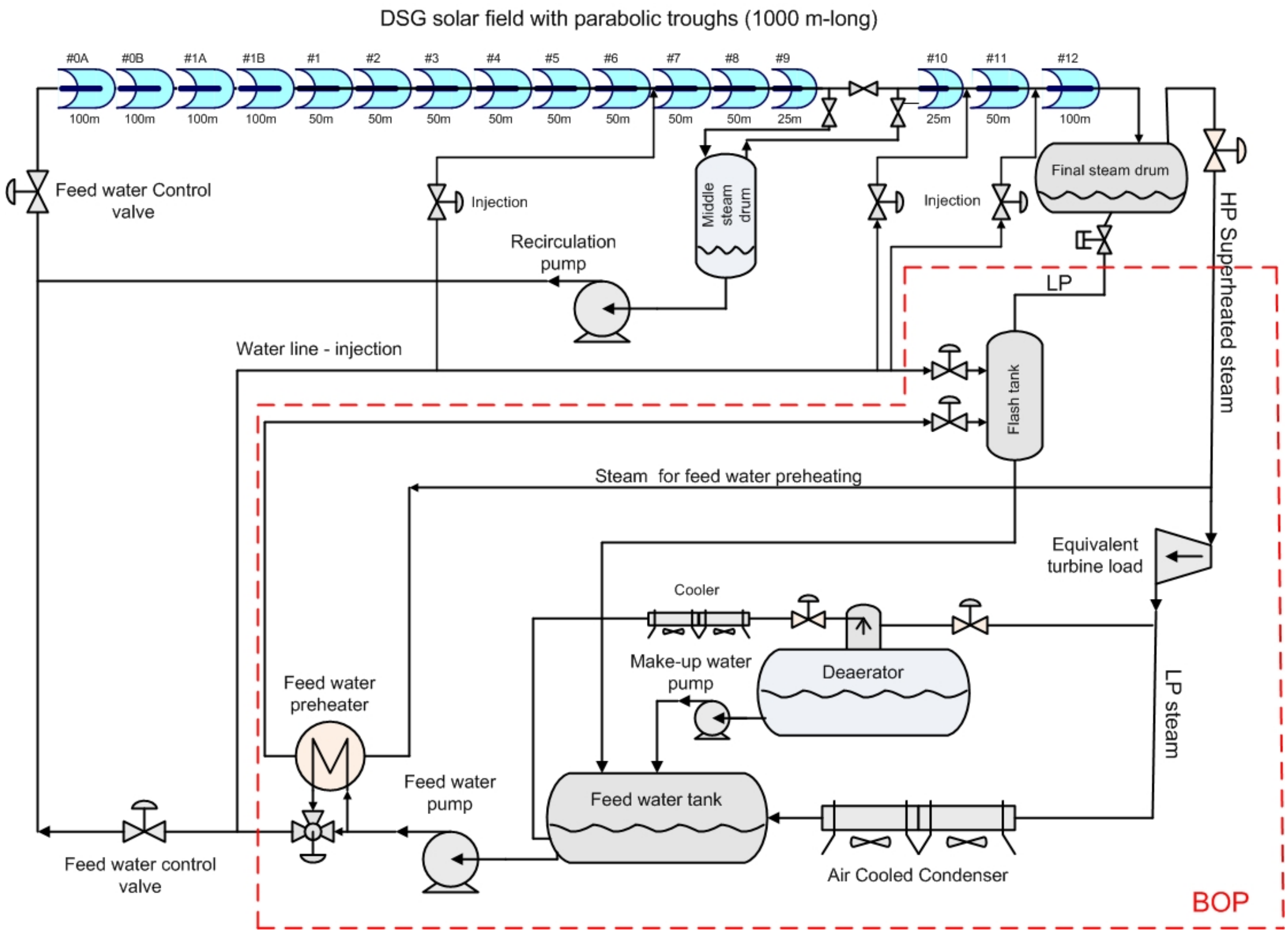


Figure 6. Simplified flow diagram of the PSA DISS loop.

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

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

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 of water/steam in horizontal tubes with non-homogeneous heat flux.

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

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 of the following components:

- New designs of parabolic-trough collectors (up to 75 m long)
- Parabolic-trough collector mirrors
- Parabolic-trough collector absorber tubes
- New designs of ball-joints or flex-hoses for connecting parabolic-trough collectors in the solar fields.
- Solar tracking systems.

The facility consists of a closed thermal-oil circuit connected to several solar collectors of 75-m long connected in parallel (up to three collectors can be installed in parallel), being able to operate only one at a time (see simplified diagram of the facility in Figure 8). The east-west rotating axis of the solar collectors increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The thermal oil used in this facility (Syltherm 800®) has a maximum working temperature of 420°C and a freezing point of - 40°C.

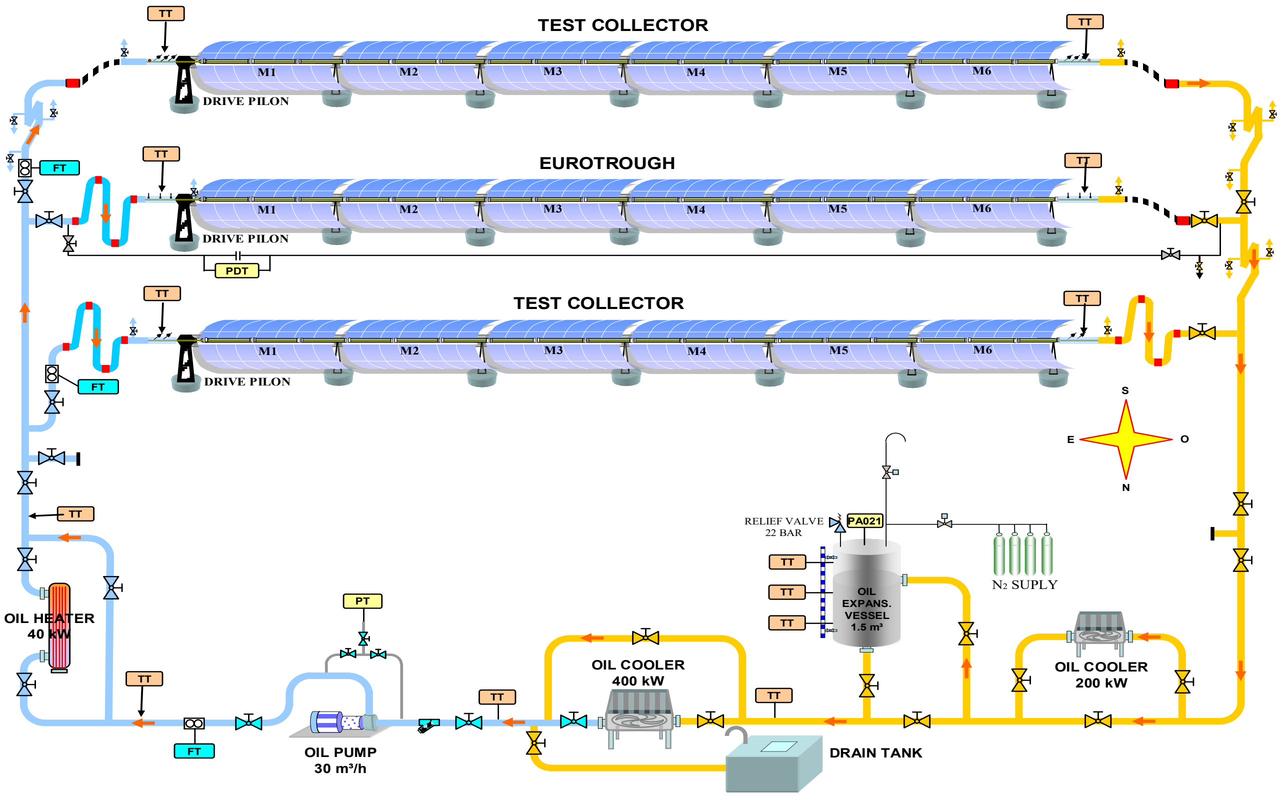


Figure 8. Diagram of the HTF test Loop located at the PSA.

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

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

Main activities at the HTF test loop are related to 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 The Parabolic Trough Test Loop (PTTL) facility

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

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

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

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

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

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

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

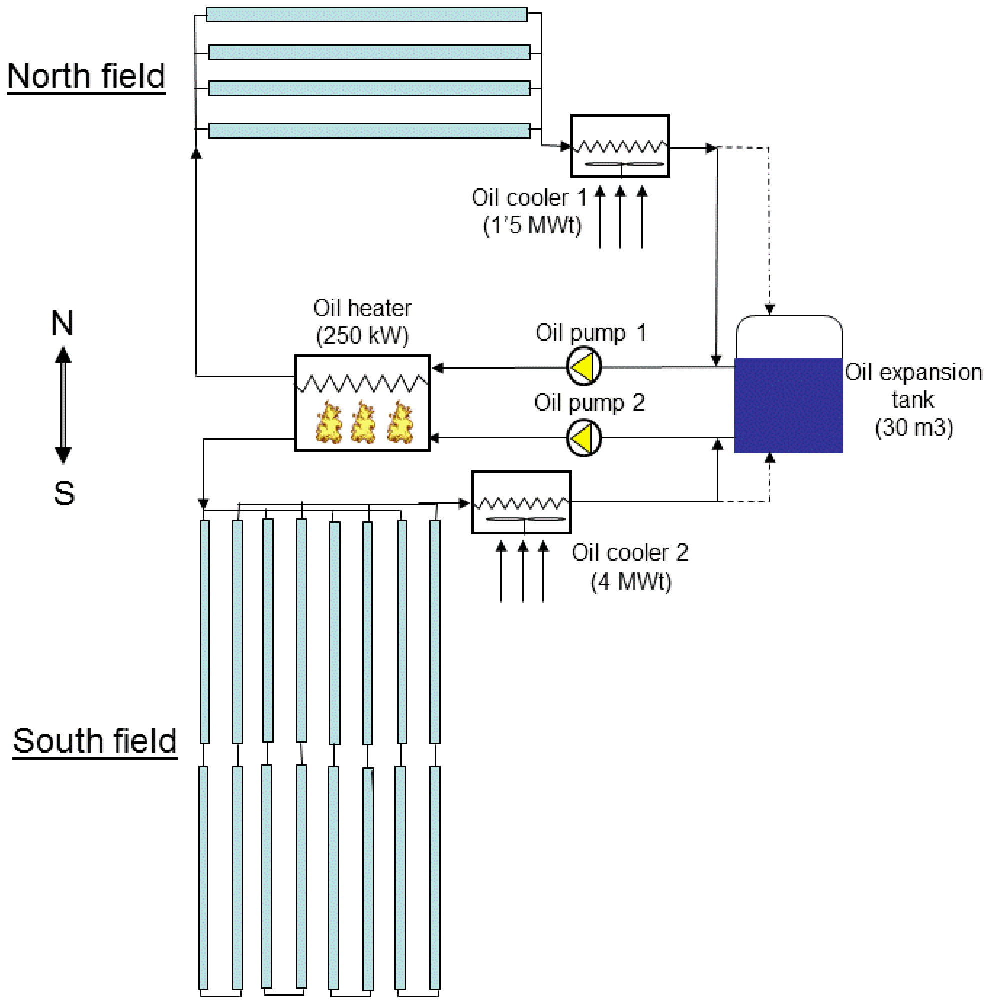


Figure 9. Simplified scheme of the PTTL facility

2.1.4 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 along the following year. The pilot plant was transferred to CIEMAT to be used as testing loop.

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

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

Figure 10. View of the PROMETEO test facility.

2.1.5 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 oil.

The TCP-100 solar field is composed of six parabolic-trough collectors, model TERMOPOWER, installed in three parallel loops, with two collectors in series within each loop, see Figure 11. Each collector is composed of eight parabolic trough modules with a total length of 100 m and a parabola width of 5.77 m. The total solar collecting surface of each collector is 545 m^2. The focal distance is 1.71 n, the geometrical intercept factor is ≥0.95, and the peak optical efficiency is 77.5%. The receiver tubes used in this solar field were delivered by 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.

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 houses the equipment necessary for its control and data acquisition.

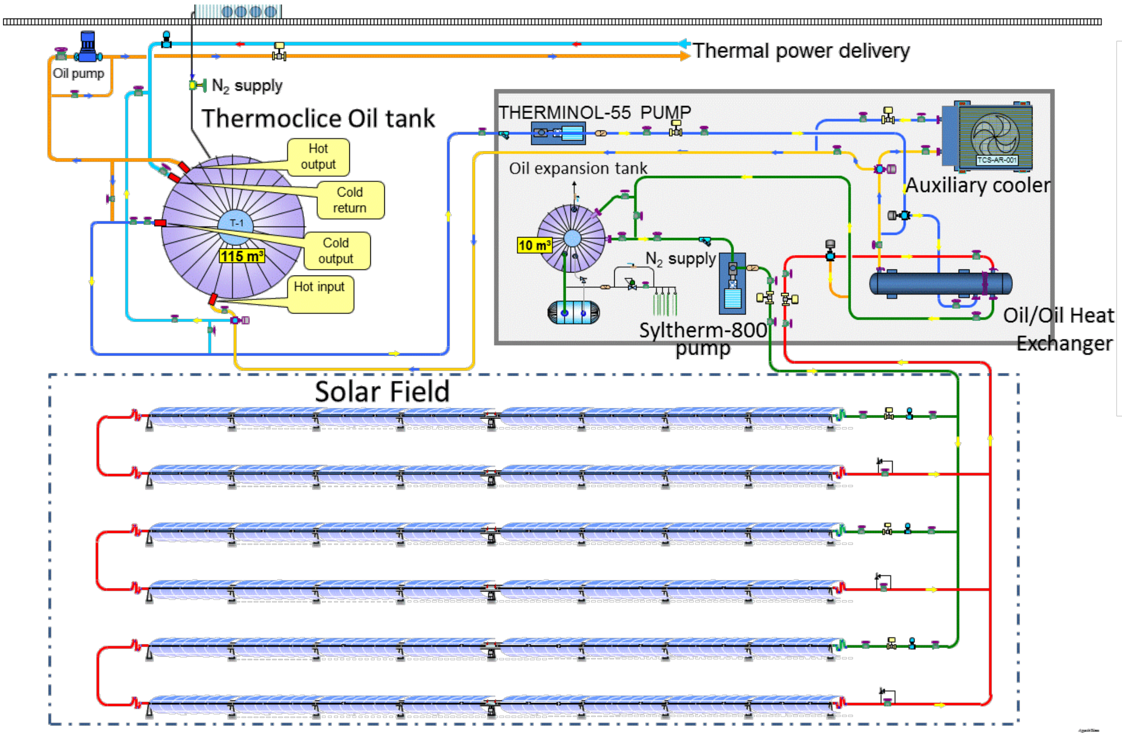


Figure 11. Diagram of the TCP-100 2.3 MWth parabolic-trough facility

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

The IFL facility was originally designed to work at pressures and temperatures of up to 100 bar and 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 gas flow rate necessary to cool the receiver tubes adequately.

- A data acquisition and control system that allows the temperature, flow rate, pressure, beam solar irradiance and humidity in the system to be completely monitored.
- Automatic control valves that allow precise, safe variation in the collector fluid feed flow rate.
- An auxiliary circuit for filling the main test loop with the gas used as heat transfer fluid.

Since testing at 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).

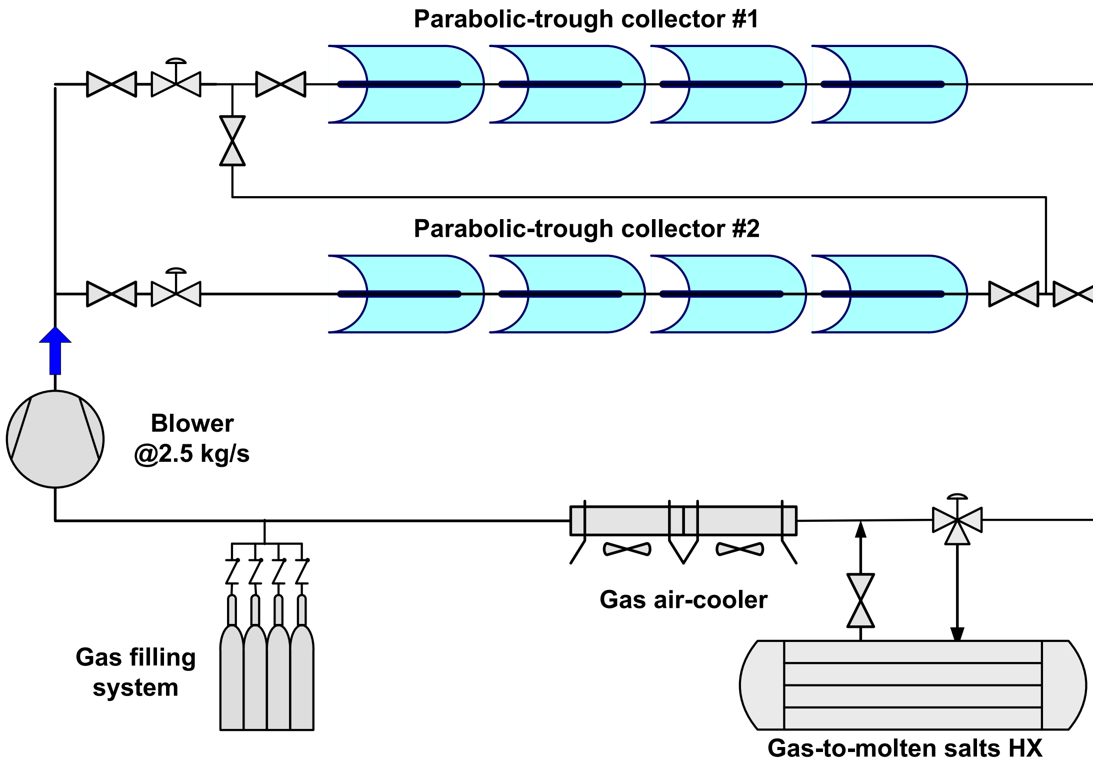


Figure 13. Simplified system diagram of the IFL experimental facility located at the PSA.

2.2 Installations associated with Parabolic Trough Systems

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 institutes.

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

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

The collector module is connected to a heating and cooling unit, which is also situated on the platform. A pump circulates *Syltherm 800®* thermal oil as heat transfer fluid (HTF) with a mass flow similar to that of commercial plants. Mass flow is measured directly using the Coriolis measuring principle avoiding uncertainties of the density. The heating and cooling unit dissipates the energy the hot HTF collected on the way through the module and ensures a constant HTF temperature (±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 14. Side view of KONTAS test bench and the heating cooling unit.

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

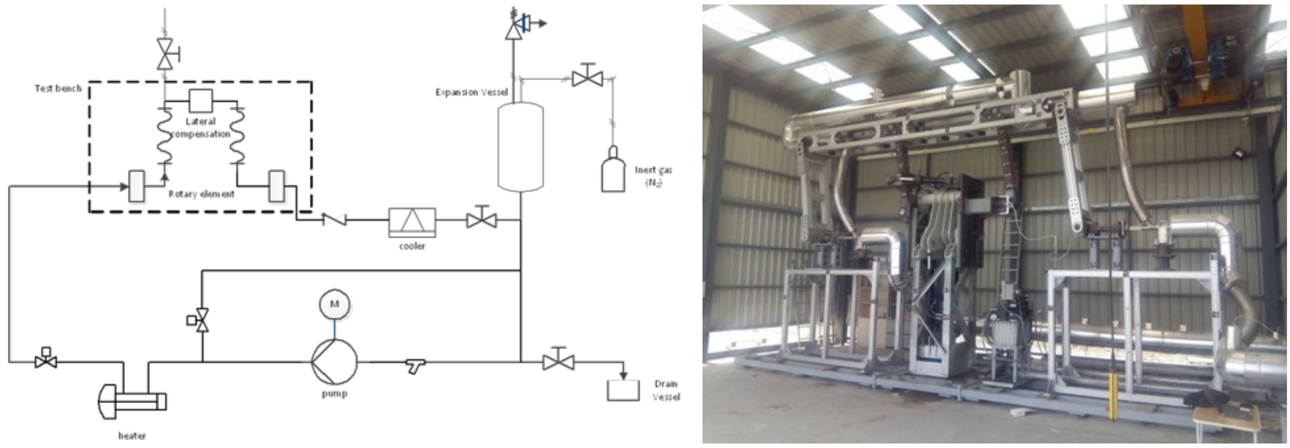
The REPA test facility is the result of merging CIEMAT activities in Task 14.4 of the European project SFERA-II (finished in 2017) and DLR activities within the national German project StaMeP. The facility is now used by CIEMAT and DLR in the framework of a joint collaboration.

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 15.a).

The balance of plant unit is composed of a variable speed HTF pump which circulates the HTF through a pipe with an adapted electrical heater collar type before passing through 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 15.b) is prepared to accommodate test samples of ball joints and flexible hoses with varying and adjustable geometries, e.g. focal lengths. It is prepared to accomplish both rotational and translational movements with the following characteristics:

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



(a) (b)

Figure 15. Schematic diagram of the REPA test loop at PSA (a) and north view of the test facility (b).

2.3 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.

2.3.1 The 6 MWth CESA-1 Plant

The CESA-1 plant (see Figure 16) was inaugurated in May 1983 to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the

CESA-1 plant is a very flexible facility operated for testing subsystems and components such as heliostats, solar receivers, thermal storage, solarized gas turbines, control systems and concentrated high flux solar radiation measurement instrumentation. It is also used for other applications that require high photon concentrations on relatively large surfaces, such as in chemical or high-temperature processes, surface treatment of materials or astrophysics experiments.

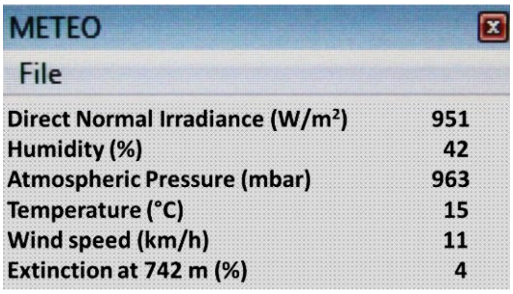
Figure 16. The CESA-I facility seen from the north.

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-1 facility has the most extensive experience in glass-metal heliostats in the world, with first generation units manufactured by SENER and CASA as well as second generation units with reflective facets manufactured by ASINEL and third generation facets and prototypes developed by CIEMAT and SOLUCAR. Despite its over 20 years of age, the heliostat field is in good working condition due to a strategic program of continual mirror-facet replacement and drive mechanism maintenance and replacement.

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

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

Currently, the measure of solar extinction is available on-line in the control room of the CESA-1 facility at PSA, facilitating the daily operation tasks (Figure 17). 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 taken simultaneous images of the same Lambertian target at very different distances using two identical optical systems with suitable digital cameras, lenses and filters.



METEO

File

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

Figure 17. On-line measurement of the solar extinction in the control room of CESA-1 facility at PSA.

2.3.2 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 devoted to testing small solar receivers in the 200 to 500 kWth capacity range.

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

Figure 18. Aerial view of the experimental SSPS-CRS facility.

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. This first autonomous heliostat field, which does not require the use of channels or cabling, was made possible by financial assistance from the Spanish Ministry of Science and Technology's PROFIT program.

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

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

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

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

Figure 19. An autonomous heliostat in the SSPS-CRS field.

2.3.3 AORA Solar Tower facility

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

Figure 20. General view of the AORA solar tower facility.

2.4 Parabolic DISH Systems

2.4.1 Accelerated ageing test bed and materials durability

This installation consists of 4 parabolic dish units, 3 DISTAL-II type with 50 kW total thermal power and two-axis sun tracking system, and 1 DISTAL-I type with 40 kW total thermal power and one-axis polar solar tracking system. In the 4 dishes, the initial Stirling motors have been replaced by different test platforms to put the materials or prototypes at small scale of high concentration receivers and perform accelerated temperature cycling. With fast focusing and defocusing cycles, the probes placed in the concentrator focus stand a large number of thermal cycles in a short time interval, allowing an accelerated ageing of the material. These platforms can be used for a large variety of applications: materials tests, air-cooled volumetric receivers tests (metal or ceramic), tests of small-size receivers prototypes with or without heat transfer fluid, etc.

The DISTAL-I concentrator (Figure 21) is a 7.5 m diameter parabolic dish, able to collect up to 40 kW_{th} energy, which is applied to the probes to obtain the accelerated ageing. The concentrator is made of a stretched membrane, which maintains the parabolic shape with a small vacuum pump. It has 94% reflectivity and can concentrate the sunlight up to 12,000 times in its 12-cm diameter focus. It has a focal distance of 4.5 m and polar solar tracking. The three parabolic dishes DISTAL-II (Figure 22) were erected at PSA in 1996 and 1997, using the stretched membrane technology. These parabolic dishes have a diameter slightly larger than the DISTAL-1 above described (8.5 m) and the thermal energy delivered in the focus is 50 kW_{th}. The focal distance is 4.1 m and the maximum concentration is 16,000 suns at the focus. These concentrators can be used for any experiment requiring a focus with the characteristics above mentioned (50 kW_{th} maximum and 16,000 suns peak concentration at the focus). The tracking consists in a two-axis azimuth-elevation system.

The test bed for durability and accelerated materials ageing is complemented with the laboratory for the assements of the durability and carachterization of materials under concentrated solar radiation existing at PSA, which is described in the laboratories section of this document (section 3.4), and with the durability and accelerated materials ageing laboratory existing at Madrid (section 3.7).

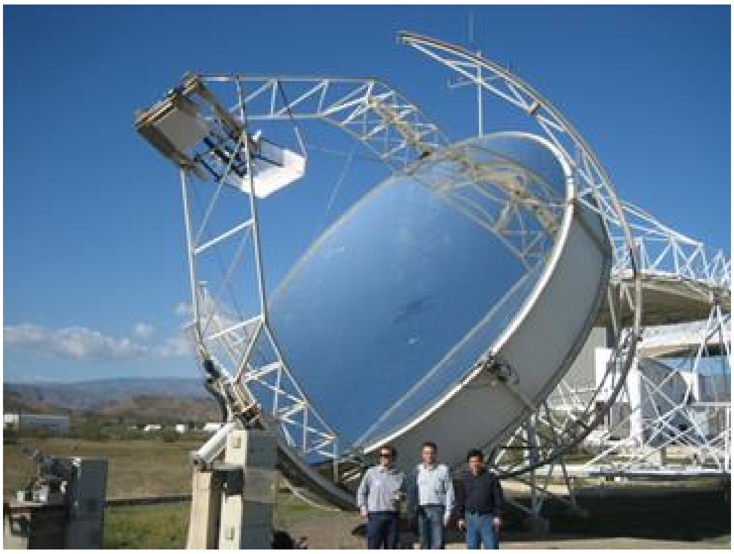


Figure 21. View of a parabolic-dish DISTAL-I used for accelerated materials ageing at PSA.

Figure 22. View of a parabolic-dish DISTAL-II.

2.4.2 EURODISH

Under the Spanish-German EUROdish Project, two new dish/Stirling prototypes were designed and erected (see Figure 23), discarding the stretched-membrane technology and applying a moulded composite-material system. These parabolic dishes can be used to test new prototypes of Stirling engines, or to perform any other test requiring a focus with 50 kWth maximum and a maximum concentration of 16,000 suns at the focus. The tracking system is azimuth-elevation.

2.5 Installation of Solar Furnaces

2.5.1 SF-60 Solar Furnace

The SF60 consists basically in a 120 m^2 flat heliostat that reflects the solar beam onto a 100 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, a test table movable on three axes is used to place the specimens in the focus.

In this furnace, the heliostat collects solar radiation and redirects it to the concentrator. The heliostat's reflective surface is made up of flat, non-concentrating facets, which reflect the sun's rays horizontally and parallel to the optical axis of the parabolic-dish concentrator, continuously tracking the sun.

Figure 23. Front and back views of the EURODISH.

The only heliostat associated with the SF-60 consists of 120 flat facets, with 1 m^2 reflecting surface each. These facets have been designed, manufactured, assembled and aligned by PSA technicians. Every facet is composed of a 1 m^2 reflecting surface and 3 mm thick Rioglass flat mirror silvered on its back (second surface mirror). Solar Furnace Technicians are also responsible of a new method of fixation of the facet on a frame that minimizes deformation of the reflecting surface. Figure 24 and Figure 25 show the heliostat installed in this solar furnace and a detail of the back side of the facet, respectively.

Figure 24. HT120 heliostat with new PSA facets.

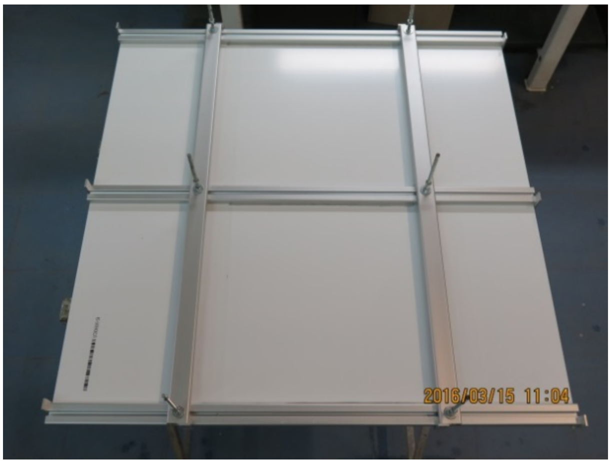


Figure 25. Back side of facet.

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

The shutter (attenuator, see Figure 26) consists of a set of horizontal louvers, which turn on their axis to control the amount of sunlight incident on the concentrator. The total energy in the focus is proportional to the radiation that goes through the shutter.

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

The combination of all the components described lead to the flux density distribution in the focus which is what characterizes a solar furnace. This distribution usually has a Gaussian geometry and is characterized by a CCD camera hooked up to an image processor and a lambertian target. The characteristics of the focus with 100% aperture and solar radiation of 1,000 W/m^2 are: peak flux, 300 W/cm^2, total power, 69 kW, and focal diameter, 26 cm.

Figure 26. HT120 heliostat in tracking.

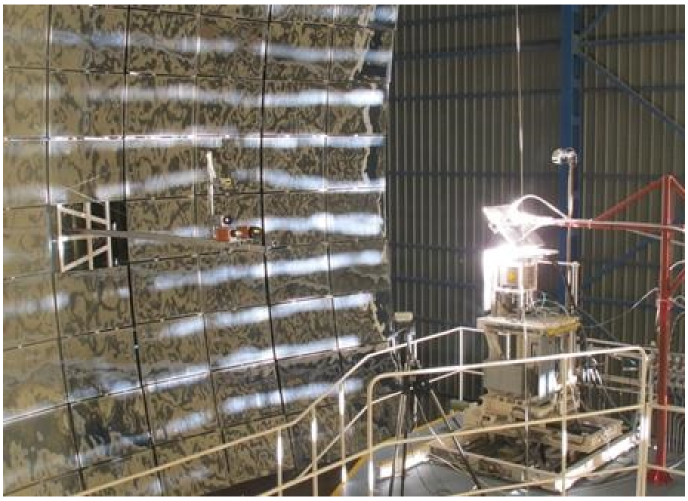


Figure 27. Interior view of the PSA SF-60 Solar Furnace in operation.

2.5.2 SF-40 Solar Furnace

The SF-40 furnace consists mainly of an 8.5-m-diameter parabolic-dish, with a focal distance of 4.5 m (see Figure 28). The concentrator surface consists of 12 curved fiberglass petals or sectors covered with 0.8-mm adhesive mirrors on the front. The parabola thus formed is held at the back by a ring spatial structure to give it rigidity and keep it vertical. The new SF40 solar furnace reaches a peak concentration of 5,000 suns and has a power of 40 kW, its focus size is 12 cm diameter and rim angle a= 50.3°. Its optical axis is horizontal, and it is of the “on-axis” type that is parabolic concentrator, focus and heliostat are aligned on the optical axis of the parabola.

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

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

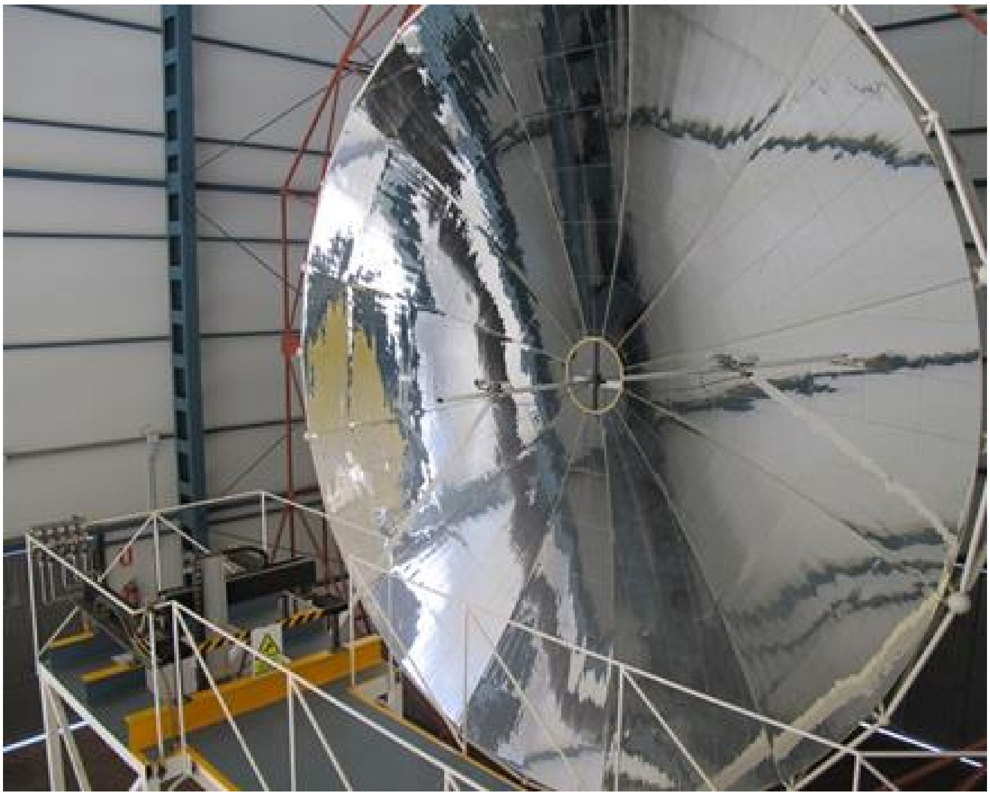


Figure 28. Interior of the SF-40 solar furnace, showing the parabolic concentrator.

2.5.3 SF-5 Solar Furnace

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

It is called SF5 -Solar Furnace 5, by its 5 kW power-, reaches concentrations above 7,000 suns, its focus diameter is 2.5 cm, and is mainly devoted to heat treatment of materials at high temperature, under vacuum and controlled atmosphere conditions, for which a vacuum chamber, called Spherical Chamber, provided with a gas system is used.

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

It basically consists of a 8.7 m^2 concentrator mirror, placed upside-down with the reflecting surface facing the floor, on a 18 m high metallic tower; in the centre of the base of the tower there is a 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 louver attenuator is placed.

Figure 29. Concentrator of the SF-5 Furnace.

2.6 Thermal Storage Systems

2.6.1 Molten Salt Test Loop for Thermal Energy Systems

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

- Two tanks, one vertical, for hot molten salts, and another horizontal, for cold molten salts.
- A thermal oil loop that can be used for heating the salt up to 380°C and cooling it down to 290°C.
- Two flanged sections, where different components for this type of loops (e.g. flow meters, heat trace, pumps…) can be tested.

Being a setup, which is similar to a commercial two-tank molten salt storage system on a reduced scale, everything related to this type of systems can be tested in this facility. 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 30. Molten Salt (MOSA) Test Loop for Thermal Energy Systems.

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 feedwater flow rate, the distillate production is 3 m^3/h, and the thermal consumption of the plant is 190 kW_{th}, with a performance ratio (number of kg of distillate produced per 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 energy collected is then transferred to the storage system. The hot water from this storage system provides the MED plant with the thermal energy required for its operation.

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

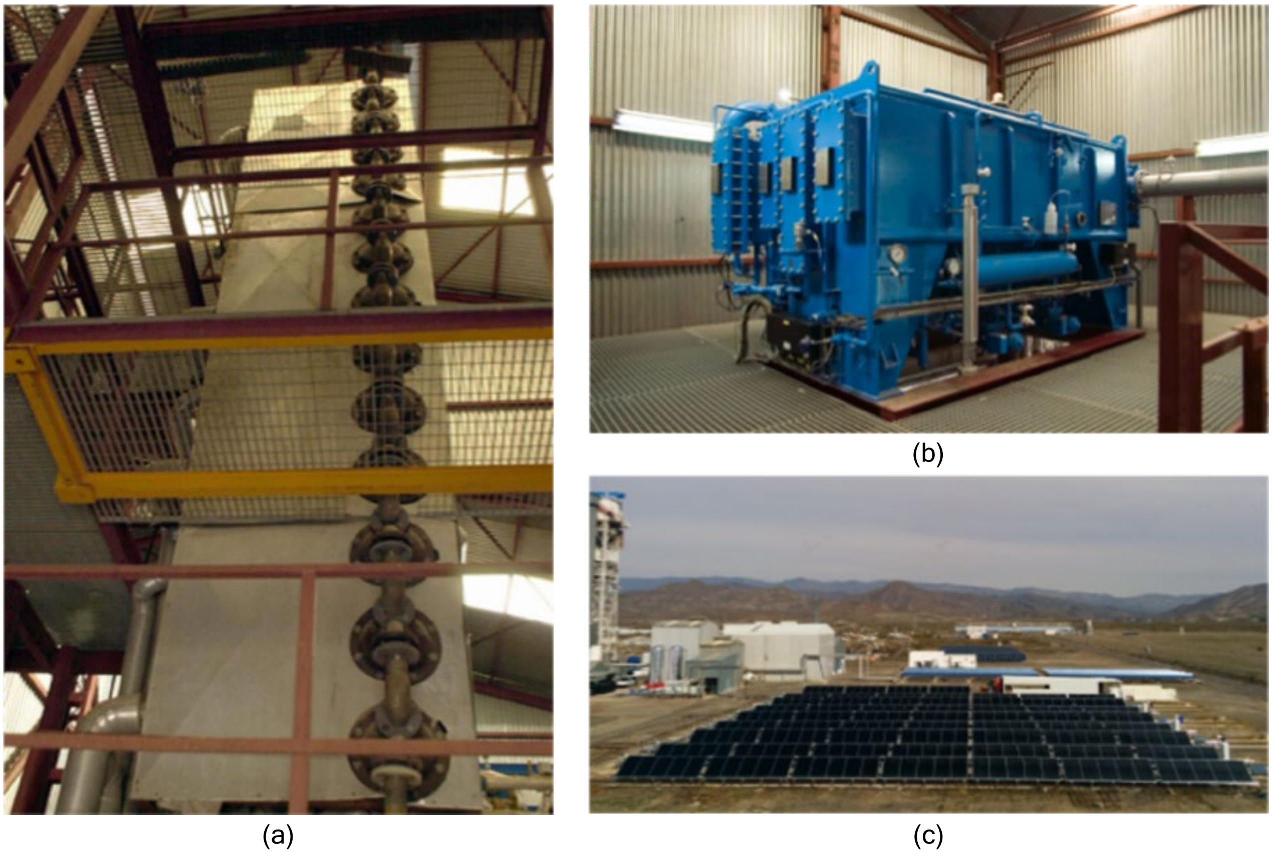


Figure 31. The PSA SOL-14 MED Plant (a) double-effect LiBr-H_2O absorption heat pump (b) and 606-m^2 flat plate solar collector field (c).

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

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 minisat 60-90°C temperature levels.

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

global irradiance and 75°C as average collector temperature). It consists of 4 loops with 14 large-aperture flat plate collectors each (two rows connected in series per loop with 7 collectors in parallel per row), and one additional smaller loop with 4 collectors connected in parallel, all of them titled 35° south orientation. Each row has its own filling/emptying system consisting of two water deposits, from which the heat transfer fluid is pumped to the collectors at the beginning of the operation and where all the water volume in the collectors is spilt either at the end of the operation or when a temperature limit is reached (above 100°C). The solar field has flow control valves that allow having an equal distributed flow rate without further regulation. Besides, the facility has an air cooler that allows the entire energy dissipation from the solar field, which is useful for efficiency tests at different temperature levels. The five loops of collectors are connected with a thermal storage system through a heat exchanger.

Figure 32. The 606-m^2 large-aperture flat plate solar collector field (AQUASOL-II).

The thermal storage system consists of two connected water tanks for a total storage capacity of 40 m^3. This volume allows sufficient operational autonomy for the fossil backup system to reach nominal operating conditions in the desalination plant.

The 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 devoted to the research of the coupling between concentrating solar power (CSP) plants and Desalination (CSP+D). The testing facility is composed of two steam generators (250 kW and 500 kW) fed by thermal oil coming from a parabolic trough solar field able to deliver thermal oil with temperatures up to 400°C and an auxiliary electrical power system that raises the temperature if required. The steam generators can produce steam at different pressures, which allow recreating any of the typical intermediate extractions or the exhausted steam available at a turbine of a thermal power plant. The low-pressure steam is obtained by making the steam from the generators to flow through two different pipe sections (12-inch diameter) equipped with control valves, which allows achieving saturated steam at two different levels: 0.074 bar/42°C (nominal flow rate of 119 kg/h, maximum flow rate of 360 kg/h) and at 0.16 bar/58°C (nominal flow rate of 195 kg/h, maximum flow rate of 360 kg/h). Both, the high- and low-pressure steam can be used as motive and entrained vapour, respectively, in a train of four steam ejectors coupled to the PSA MED plant, simulating the behaviour of a MED plant working with thermal vapour compression (TVC-MED). The steam ejectors can work in a wide range of pressure conditions for the motive steam (40 - 6 bar; 4 - 2 bar), which also makes this test bed useful for the characterization of such kind of devices. The low-pressure steam can also be condensed through two conventional air condensers without passing by the steam ejectors, with the aim of allowing research in CSP cooling topics. The flexibility of the test facility also allows the on-site evaluation of innovative dry coolers prototypes for their comparison with respect to the conventional air condensers currently available at the market.

(a) (b)

Figure 33. View of the outside of the CSP+D test bed building with the air coolers (a) and partial view of the interior of the CSP+D test bench (b).

2.7.2.2 NEP: The facility for Polygeneration Applications

Polygeneration is an integral process for the purpose of producing two products from one or several resources. In the case of solar energy, it makes use of the thermal energy from a solar field for several simultaneous applications, such as generating electricity, desalting water for drinking water supply and the rest for 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 requiring temperatures around 200°C. The collector selected was the Polytrough 1200 prototype by NEP Solar. It has a production of 15.8 kW per module (0.55 kW/m^2) under nominal conditions, with a mean collector temperature of 200°C, and efficiency over 55% in the range of 120-220°C (for 1000 W/m^2 of direct normal irradiance).

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

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

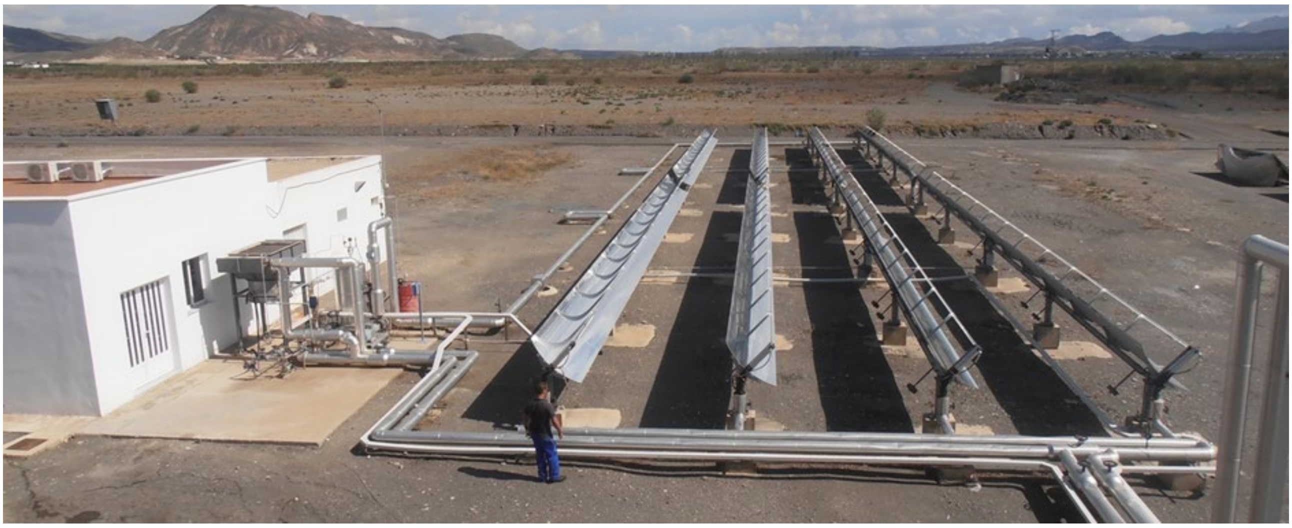
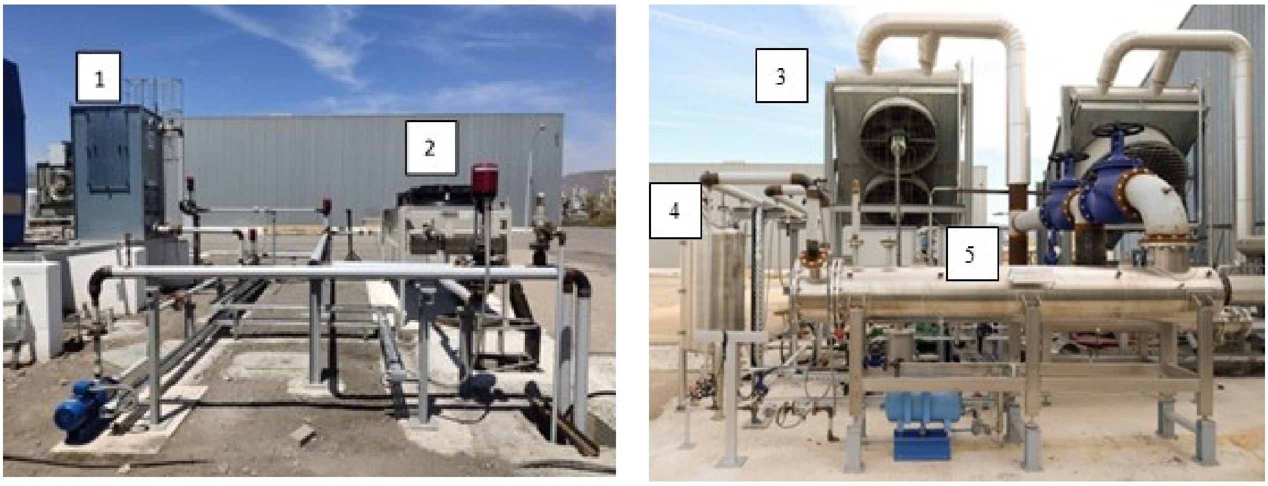


Figure 34. NEP PolyTrough 1200 solar field.

2.7.2.3 Hybrid-cooling pilot plant

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

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



(a) (b)

Figure 35. 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).

2.7.3 Membrane Desalination Test Facilities

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

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

The installation has a separate water circuit that can be used for cooling (about 3.5 kW_{th}) in the desalination units and as a device for supplying simulated seawater, with the possibility of working in an open or closed loop. In the latter case, both the distillate and brine flows are collected and mixed 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 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).

(a) (b)

Figure 36. Internal (a) and external (b) views of the Membrane Distillation experimental test bed within the PSA low-temperature solar thermal desalination facility.

2.7.3.2 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 37) that can be used for evaluating direct-contact, air-gap or permeate-gap membrane distillation. The module is made of polypropylene and designed so that the membrane can be replaced very easily. The module has a condensation plate on the cold side to operate on air-gap configuration, but it can be closed at the bottom to operate on permeate-gap keeping the distillate inside the gap or spared to operate on direct-contact mode. The effective membrane surface is 250 cm^2.

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

2.7.3.3 Bench-Scale Unit for Flat Sheet Membrane Distillation Testing

The facility is a high precision laboratory grade research equipment (Figure 38) designed for testing fundamental and feasibility test trials on membrane distillation. It possesses the following unique features that are essential for representative and scalable results:

1) Cell format with representative flow distribution. The cell size is sufficient for flow distribution and regime to be applicable to full-scale MD technology.
2) Adjustable MD channel configuration to all channel variants (PGMD, AGMD, DCMD, VMD, VAGMD).
3) Temperature precision of 0.5°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 37. Bench-scale unit for testing membranes on isobaric MD.

Figure 38. Bench-scale unit for testing MD with flat-sheet membranes.

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

The installation consists of a test bed with two small plate and frame modules of forward osmosis (FO) which can be connected in series or parallel. There is, therefore, one pump for the draw solution and two for the feed solution, each with variable flow and flow-rate measurements. The hydraulic circuit has been modified so that the modules can be operated in pressure-retarded osmosis (PRO) mode. For that purpose, steel pipes and a high-pressure pump (3 L/min; up to 17 bar) are installed in the draw side, and cells with operational pressure up to 15 bar are used. The cells each have a total effective membrane area of 100 cm^2, and hydraulic channels in zigzag 4 mm wide and 2 mm deep.

The system uses one container for the draw solution and two for the feed solutions, each placed on a balance in order to measure changes in the mass flow rates of the draw solution and the feed solution of each cell. The containers have an automatic dosing system to keep the salinities constant. The system has two conductivity meters for low salinity and one for high salinity, as well as pressure gauges in each line and temperature readings.

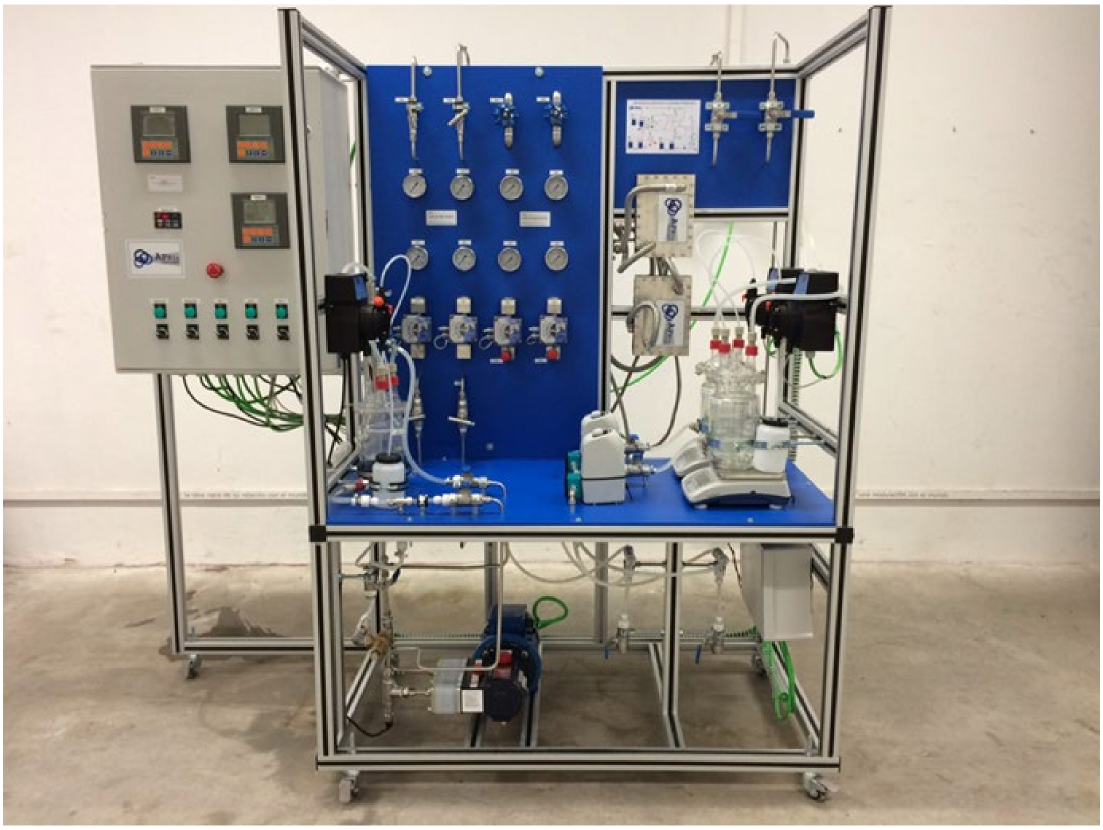


Figure 39. Bench-scale unit for testing FO and PRO.

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

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

Figure 40. Test bed for FO-RO combination research.

2.8 Experimental Solar Detoxification and Disinfection Installations

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

- Solar CPC (compound parabolic collector) pilot plants.
- Solar simulators.
- UVC-pilot plant.
- 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 Solar CPC pilot plants

Since 1994 several CPC pilot plants have been installed at PSA facilities (Figure 41). Basically, the solar pilot plants are built by modules which can be connected in series. Each module consists of a number of photo-reactors placed on the focus of an anodized aluminum mirror with Compound Parabolic Collector (CPC) shape to optimize solar photons collection in the photo-reactor tube. The modules are place on a platform titled 37° from the horizontal to maximize the global solar collection of photons through the year. In addition, the pilot plants are equipped with added systems for different purposes, for example: sedimentation tanks (for catalyst recovery), heating and cooling systems for temperature control during the experiments, coupling with other treatment technologies like bio-treatment, ozonation, etc. A summarize of the already installed solar CPC reactors is shown in **¡Error! No se encuentra el origen de la referencia.**.

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

Year	CPC (m^2)	Total/illuminated volume (L)	Flow or static	Tube diameter (mm)	Added systems/Characteristics
1994	3x3	250/108	Flow	50	
2002	15	300	Flow	32	
2004 (CADOX)	4	75/40	Flow	50	- 50L ozonation system - Biological water treatment system - Monitoring (pH, T, ORP, O_2, flow rate, H_2O_2, O_3), control (pH, T, flow rate)
2007 (SOLEX)	3.08(x2)	40/22	Flow	32	- Twin prototypes - Plexiglass screen - Monitoring dissolved O_2 and temperature - Specially developed for photo-Fenton applications
2008 (FIT)	4.5	60/45	Flow	50	- Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), flow rate). - 100 L sedimentation tank for catalyst separation
2010 (FIT-2)	4.5	60/45	Flow	50	- -Monitoring (pH, T, O_2, flow rate) and control (T (20-55°C), O_2, flow rate) - -Sedimentation tank
2011 (HIDRO-CPC)	2.1	25/14.24	Flow	32	- -Coupled with H_2 generation pilot plant
2011 (CPC25)	1	25/11.25	Flow	50	
2013 (ELECTROX)	2	40/25	Flow	50	- Coupled with electro-photo-Fenton plant
2013 (NOVO75)	2	74/68.2	Flow	75	- Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate)
2013 (CPC25)	1	25/11.25	Flow or static	50	- Variable volume, versatile for different volume of water
2013 (SODIS-CPC)	0.58(x2)	25/25	static	200	- Low cost, no recirculation system
2016 (NOVO 75 V1.0)	2.03 (x2)	34 or 53	Flow or static	75	- Two modules of collectors: CPC versus U-mirror type alternatively used - Tubes installed in vertical position - Air injection in tubes - Monitoring (pH, T, O_2, flow rate) and control (T, O_2, flow rate) - - Automatic control system for filling the system accordingly to incident energy - - Solar panel for water heating

As mentioned in table 1, CADOX photoreactor was hooked up to a 50 L-ozonation system with an ozone production up to 15 g O_3/h. It is completely monitored (pH, T, ORP, O_2, flow rate, H_2O_2, O_3) and controlled (pH, T, flow rate) by computer. Besides, and connected to this photo-reactor, there is a biological water treatment system consisting of three tanks: a 165 L conical tank for wastewater conditioning, 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)

(b)

Figure 41. View of several CPC photo-reactors for purification of water. a) CPC facilities I, b) CPC facilities II.

A 2 m^2 CPC collector (Figure 42) with 10 borosilicate glass tubes (50 mm diameter), 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 shape (CPC and U mirror type) has been installed at PSA (Figure 43). 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 permits to increase water temperature prior to fill in the photoreactors.

Figure 42. View of 2 m^2-CPC coupled to Electro-Fenton pilot plant (ELECTROX).

Figure 43. View of new CPC and U-type photoreactors (NOVA 75 V 1.0).

2.8.2 Solar simulators

Along with these pilot-plant facilities, there are two solar simulators provided with xenon lamps for small-scale water decontamination and disinfection experiments. In both systems, the radiation intensity can be modified and monitored. One of the solar simulators XLS+ contains a UV filter (Suprax) with wavelength limitation to 290 nm simulating external solar radiation. Temperature can be also modified and controlled in both systems by a cooling system (SUNCOOL) (Figure 44).

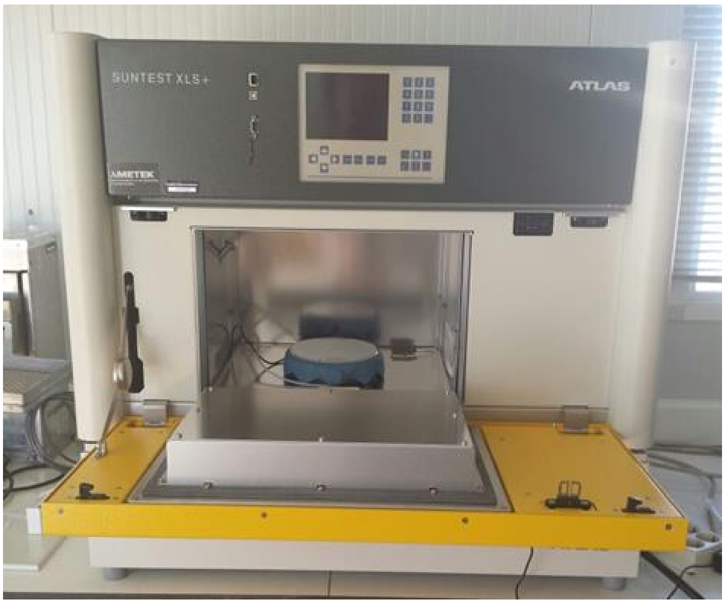


Figure 44. Solar simulator SUNTEST XLS+.

2.8.3 Ozonation pilot plant

The ozonation system has a contact column reactor with total volume of 20 L (minimum operation volume of 8 L), reagents dosing system and pH automatic control. The pilot plant is equipped with pH and redox sensors, inserted in the recirculation line. In 2016, new instrumentation has been added to the ozonation pilot plant: (i) equipment for humidity elimination in the ozone gas outlet (Figure 45.a); (ii) Thermo-catalytic ozone destructor (Figure 45.b); (iii) dissolved ozone sensor (Figure 45.c). This ozonation system works in batch mode allowing its combination with other technologies such as CPC photoreactors and the UV pilot plant.

(a) (b) (c)

Figure 45. a) Equipment for humidity elimination in ozone gas outlet; b) Thermo-catalytic ozone destructor; (c) Dissolved ozone sensor.

2.8.4 Nanofiltration pilot plant

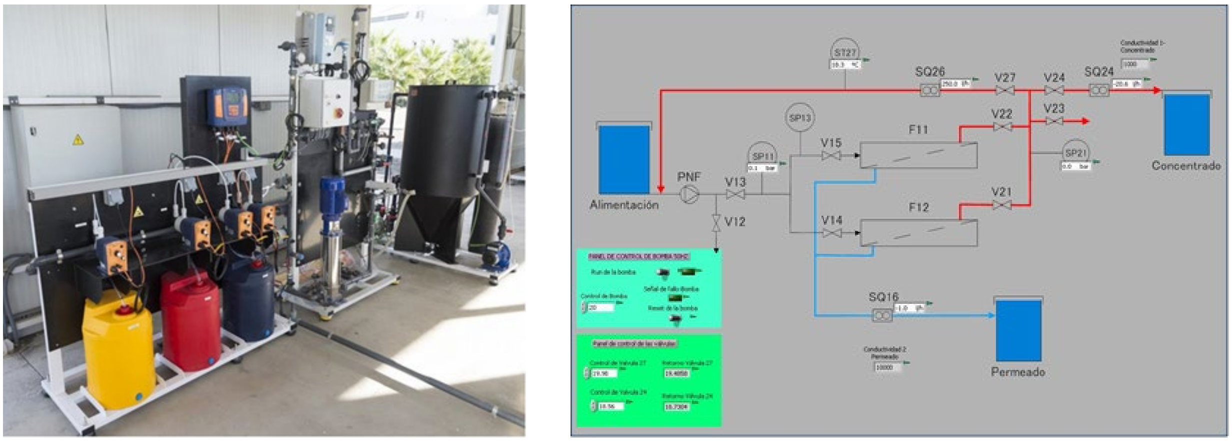
The nanofiltration (NF) system has two working modes, in series and in parallel. The basic system consisted of two FILMTEC NF90-2540 membranes, connected in parallel, with a total surface area of 5.2 m^2. These polyamide thin-film composite membranes work at a maximum temperature of 45°C, a maximum pressure of 41 bar and a maximum flow rate of 1.4 m^{3}h^{-1}, whereas operation pH range is 2-11. A third membrane was installed later and so the filtration total surface area was increased to 7.8 m^2. pH control permits the cleanings and to evaluate the separation of different compounds in the membranes depending on the pH value. A dosing pump is also included for studying the effect of biocide addition. It has a feeding tank of 400 L (Figure 46.a). In 2016 the nanofiltration system has been automatized by including electro-valves and automatic acquisition of the signals from the different instruments (flow, pressure, temperature, etc.) with the final aim of controlling by a computer (Labview interface was implemented, Figure 46.b) the generation of permeate and concentrate flow rates.

2.8.5 UVC-H_2O_2 pilot plant

Ultraviolet (UV) pilot plant was designed to treat and disinfect water for research and comparison with the solar technologies. This plant consists of three UV-C lamps (max. flow rate 25 m^{3}h^{-1}, 254 nm peak wavelength, 400 J m^{-2} max. power) connected in series, with the flexible configurations for single lamp, two or three lamps in recirculating batch mode or continuous flow mode. Lamps power and flow rate can be regulated according to the needs of the water. Furthermore, the plant is equipped with a dosage system of reactants (acid, base, and hydrogen peroxide). The total volume per batch is 200-250 L, with illuminated volume and area of 6.21 L and 0.338 m^2 per lamp module, respectively. The system is equipped with pH and dissolved oxygen sensors in-line and connected to a PROMINENT controller for automatic data acquisition of both parameters (Figure 47).

2.8.6 Photocatalytic generation of hydrogen pilot plant

This plant is connected to a CPC photo-reactor for the simultaneous removal of organic contaminants contained in aqueous solutions and hydrogen generation (Figure 48). The pilot plant consists of a stainless-steel tank with a total volume of 22 L, fitted with gas and liquid inlet and outlet and a sampling port. Two parallel mass flow controllers are used to control the desired N_2 gas flow into the reactor headspace during the filling step. The CPC photo-reactor coupled with this system was described above in **¡Error! No se encuentra el origen de la referencia.**.



(a) (b)

Figure 46. a) Nanofiltration pilot plant photo; b) New lavbiew interface for control and automatic operation of the pilot plant.

Figure 47. UVC pilot plant installed at PSA facilities.

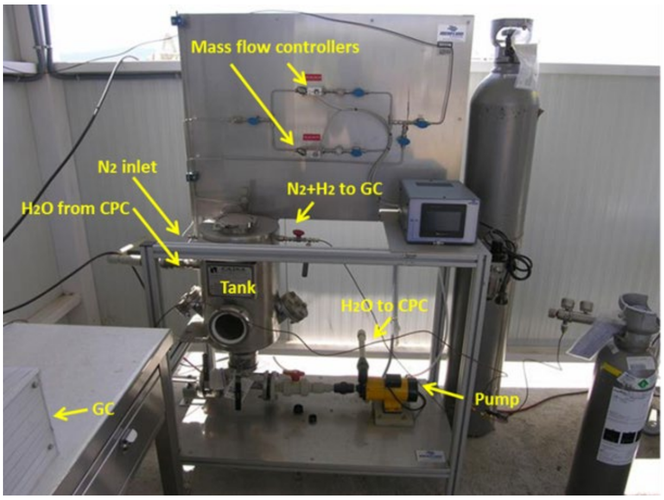


Figure 48. Solar pilot plant for photocatalytic generation of hydrogen.

2.8.7 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 pressurized the system, and the use of different metallic salts as catalyst. The Wet Air Oxidation pilot plant consists of a stainless steel reactor with a total volume of 1,000 mL, a magnetic stirrer, a breakup disk, liquid reagents injector prepared to operate under 200 bar and a maximum temperature of 300°C, thermo-probe, pressure sensor (until 250 bar) and a cooling-heating jacket, all made of stainless steel. The Wet Air Oxidation pilot plant includes an automatic system of control and data acquisition of diverse parameters such as pressure, temperature, reagents dosses and agitation velocity.

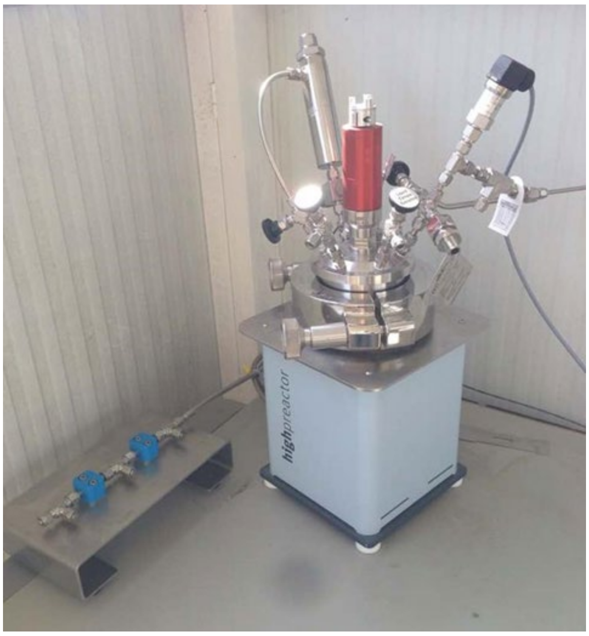


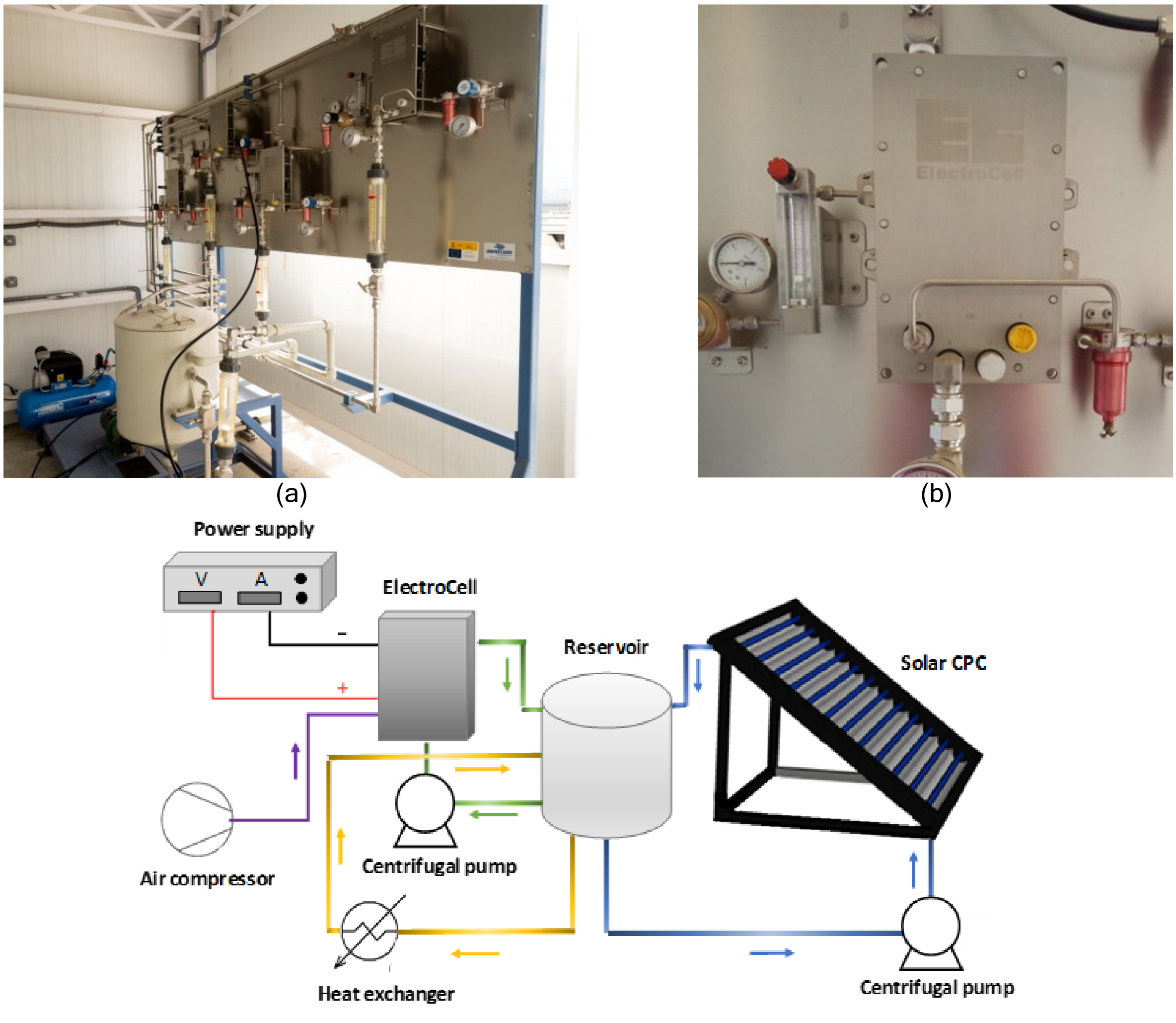
Figure 49. Wet Air Oxidation Pilot plant.

2.8.8 Electro-oxidation pilot plant

Electro-oxidation pilot plant consisted of four undivided 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).

2.8.9 Solar UVA monitoring equipment

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 the global UVA radiation in the range 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.



(c)

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.

(a) (b) (c)

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

2.8.10 Biological pilot plant

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

Figure 52. Biological pilot plant installed at PSA facilities.

2.8.11 Cultivation chamber

The culture crop chamber of 30 m^2 is used for treated wastewater re-use experience since 2014 (Figure 53). This controlled chamber is made of polycarbonate of 10 mm thick to avoid ultraviolet radiation supported by white rolled steel (Sendzimir). The shoulder height is 2.5 m with a roof slope of 40%. The camera consists of 4 individual areas of 3 m^2 x 2.5 m^2. Each area is equipped with temperature and humidity sensors, and a cooling and heating system. The crop camera is equipped with a global solar radiometer for measuring the incident solar radiation. So, through this probe an opaque plastic cover located on the top of the camera can be automatically fold and re-fold to reduce the incidence of irradiance inside the crop camera. Finally, the roof slope of each area acts as windows which can be automatically opened and closed to favour the airflow inside each area and enhance the efficiency of the temperature control. The measured of sensors (temperature, humidity and solar radiation) and temperature control of each individually area (by the cooling and heating system, windows and top plastic cover) is made using the Ambitrol® software which permits to keep a comfortable temperature for crops approximately to 25°C during the different seasons.

Figure 53. Cultivation chamber for wastewater crops irrigation reuse at PSA facilities.

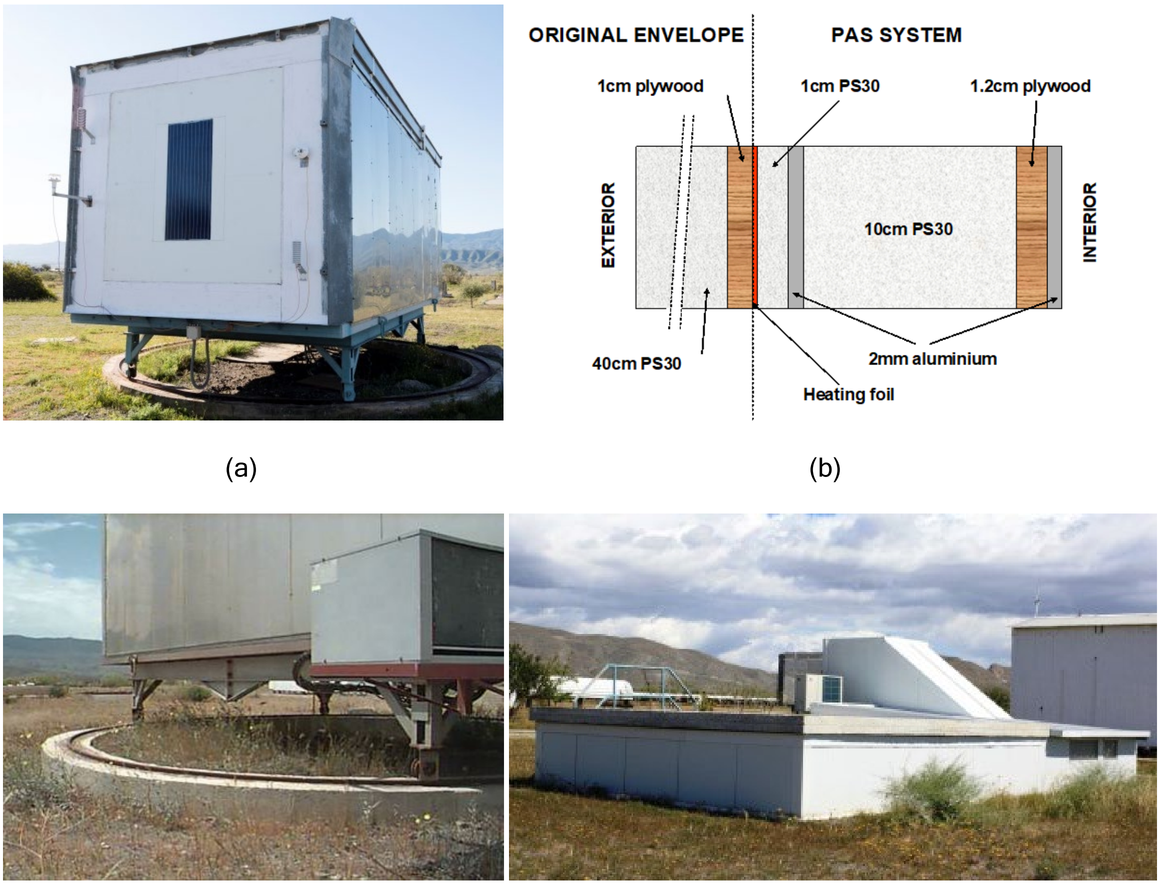
2.9 Experimental Installations for the Evaluation of the Energy Efficiency in Buildings

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

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

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

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



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

Figure 54. (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.

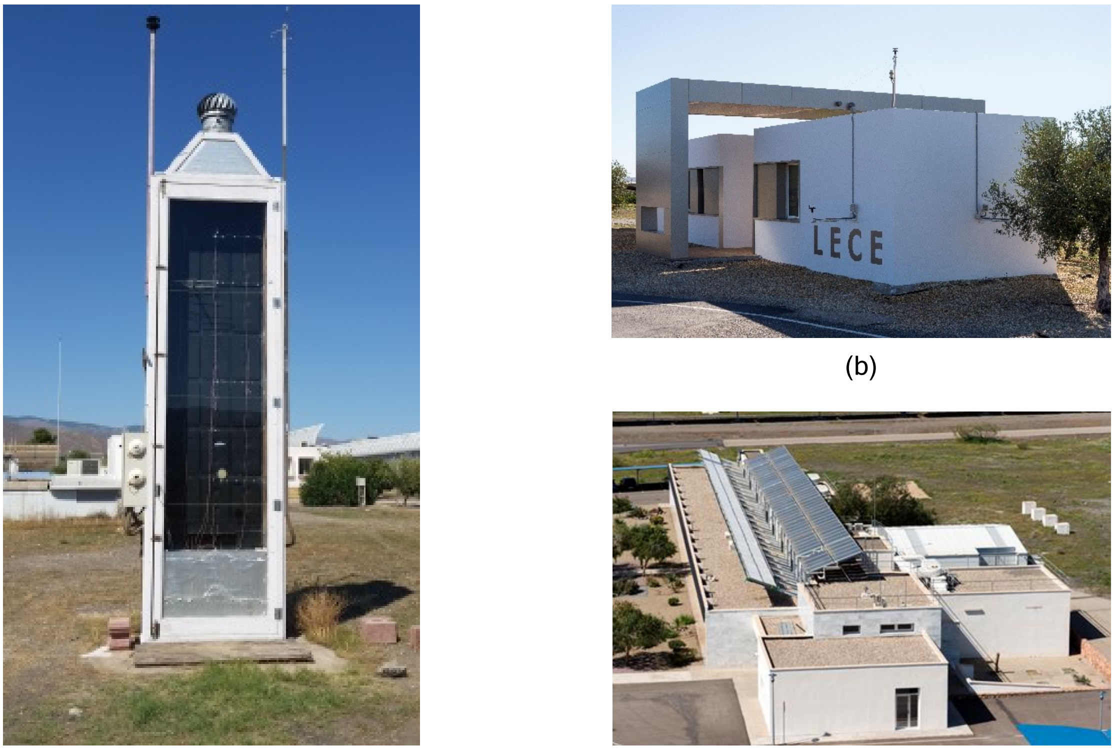
4) Solar Chimney: This was constructed for empirical modelling experiments and validating theoretical models. Its absorber wall is 4.5 m high, 1.0 m wide and 0.15 m thick, with a 0.3-m-deep air channel and 0.004-m-thick glass cover. A louvered panel in the chimney air outlet protects it from rodents 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.

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 m^2 built area. One of them is at the PSA and the others in different locations representative of Spanish climates. These C-DdIs

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

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



(b)

(a) (c)

Figure 55. (a) Solar Chimney. Configuration including Phase Change Material tiles, (b) Reference single-zone building, (c) ARFRISOL Building Prototype in use.

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.). The laboratory of the Concentrating Solar Systems Unit has a specific activity line for the geometric characterization of these concentrators. Photogrammetry is used to quantify the optical quality of:

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

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

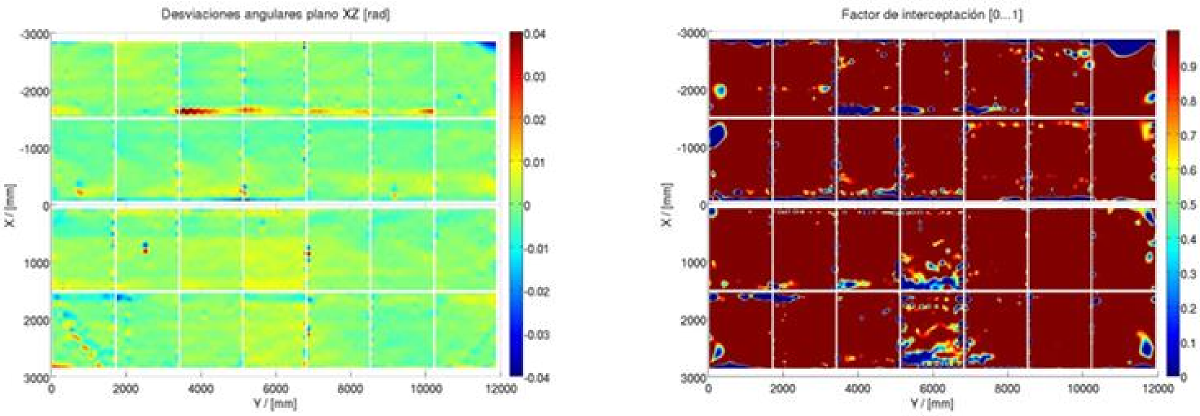
The equipment allocated to this activity at PSA is composed of:

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

Additionally, a software package for model analysis and calculation of relevant parameters for 2D and 3D geometries in the MatLab environment 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 56. Angular deviations (a) and intercept factor (b) of a parabolic-trough collector module analysed by photogrammetry.

3.2 Solar reflector durability analysis and optical characterization labs

The PSA optical characterization and solar reflector durability analysis laboratories, which are the result of a joint collaborative project between CIEMAT and DLR, have the necessary equipment to completely characterize the materials used as reflectors in solar concentrating systems. These labs allow the characteristic optical parameters of solar reflectors and their possible deterioration to be determined. The optical analysis lab has the following equipment for the optical analysis of solar mirrors (see Figure 57.a):

- Three portable specular reflectometers, Devices and Services Model 15R-USB, for measuring specular reflectance at 660 nm at different aperture angles (3.5, 7.5, 12.5 and 23 mrad).
- One portable specular reflectometer, Devices and Services model MWR, for measuring specular reflectance at 460, 550, 650 and 720 nm and at different aperture angles (2.3, 3.5, 7.5, 12.5 and 23 mrad).
- Reflectometer prototype for measuring specular reflectance in a 5 cm diameter with spatial resolution of 10 pixel/mm, which measures at various wavelengths and aperture angles (model SR^2, designed and patented by DLR).
- Perkin Elmer Lambda 1050 spectrophotometer, with 150-mm integrating sphere and specular reflectance accessory with 0 to 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 2nd solar reflector durability analysis lab is designed for accelerated ageing tests of these materials with the purpose of predicting in a short time, the behaviour of these materials during their useful lifetime (see Figure 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 simulation equipment is available for these accelerated ageing tests:

- ATLAS SC340MH weathering chamber 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 analyze the possible detachment of the paint layers.
- Several devices for thermal cycles specially designed at the PSA.

(a) (b)

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

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.

3.3 Radiometry laboratory – RadLab

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

Figure 58. 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 59. IR sensor calibration using a black body.

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

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

The equipment associated to this activity is composed of devices located both indoor and outdoor. The indoor devices are devoted to the metallographic preparation and the analysis of test pieces treated with concentrated solar radiation and eventually thermal cycling for accelerated aging, and characterization of solar test by thermogravimetry. These devices are inside the Solar Furnaces control building and located in four rooms, every one of them dedicated to different kind of analyses:

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

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

3.4.1 Metallography Room

- Automatic cut-off machine: Struers Secotom
- Manual cut-off machine: Remet TR60
- Mounting press: Struers Labopres-3
- Vacuum impregnation unit: Struers Epovac
- Polisher: Tegrapol-15 automatic with Tegradoser-5 dosing system
- Metallographic polisher 2 plates: LS1/LS2 (Remet)
- Grinder: Remet SM1000
- Ultrasonic bath: Selecta Ultrasons-H 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 60. View of the Metallography Room in the Solar Furnaces building

3.4.2 Microscopy Room

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

- Balance: Mettler Toledo classic max 320 g/min 10 mg

3.4.3 Thermogravimetry Room

- The thermogravimetric Balance SETSYS Evolution18 TGA, DTA, DSC (Temperature range ambient to 1,750°C) equipped with a compact recirculating cooler (Julabo FC1600T) and a thermostatic line to 200°C, with a security box for tests in presence of H_2, and adapted to connect a controlled evaporator mixer and a MicroGC simultaneously to the equipment. This thermogravimetic Balance has different possibilities of tests:
    - Tests under pure Hydrogen atmosphere up to 1,750°C
    - Tests under pure Oxygen atmosphere
    - Tests under H_2O steam with other gases simultaneously.
    - Tests under corrosive atmosphere up to 1,000°C
- CEM System (Controlled evaporator mixer system) for steam supply.
- Fixed Gas Detector: Dräger Polytron SE Ex, with a control system Regard 1.

(a) (b)

Figure 61. View of a) the Microscopy Room, and b) the thermogravimetric balance inside of its Room.

3.4.4 Thermal Cycling Room

It includes the instrumentation necessary for thermal cycling:

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

The indoor devices located in the four rooms described above are complemented by an electronic microscope installed in its own room, which is shared by the AMES and SCS units, and with the following specifications.

- Scanning electronic microscope (SEM) - Hitachi, model S-3400N II, high/low vacuum, secondary electron image, backscattered electron image, cooling stage and magnification 5x to 300,000x.
- Energy dispersive x-ray spectrometer (EDS) Quantax 400

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

The outdoor equipment is composed of several solar-dish concentrators located close to the PSA solar furnaces building. These solar dishes are used for thermal cycling under real solar conditions, with very high solar flux (up to 1,200 kW/m^2) and high temperatures (from 200°C to 1,200°C) and are equipped with different test benches for volumetric and tube configuration testing.

3.5 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 62.a), for measuring heat loss of single receiver tubes under indoor laboratory conditions, and b) an outdoor test bench called RESOL (see Figure 62.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 62. 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 lets to characterize heat losses of receiver tubes with inner diameter greater than 62 mm and tube length lower than 4.5 m. Measurements can be performed for absorber temperature ranging from 100°C to 500°C. The vacuum in the test chamber can be set up to around 10^{-2} mbar. RESOL is currently configured to measure standard receiver tubes for parabolic troughs, i.e. tubes 4,060 mm-long and with absorber tube diameter of 70 mm.

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

3.6 Advanced Optical Coatings Laboratory - OCTLAB

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

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

- Perkin Elmer LAMBDA 950 Spectrophotometer (Figure 63.a).
- Perkin-Elmer Frontier FTIR spectrophotometer equipped with a gold-coated integrated sphere manufactured by Pike (Figure 63.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 63.c).
- QUV weathering chamber, Q-PANEL, for accelerated ageing tests (Figure 63.d).
- BROOKFIELD LVDV-I+ Viscometer.
- BRUKER DektakXT stylus profilometer with optical camera and software for surface analysis (Figure 63.e).
- KSV CAM200 goniometer for measuring contact angles (Figure 63.f).
- 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.

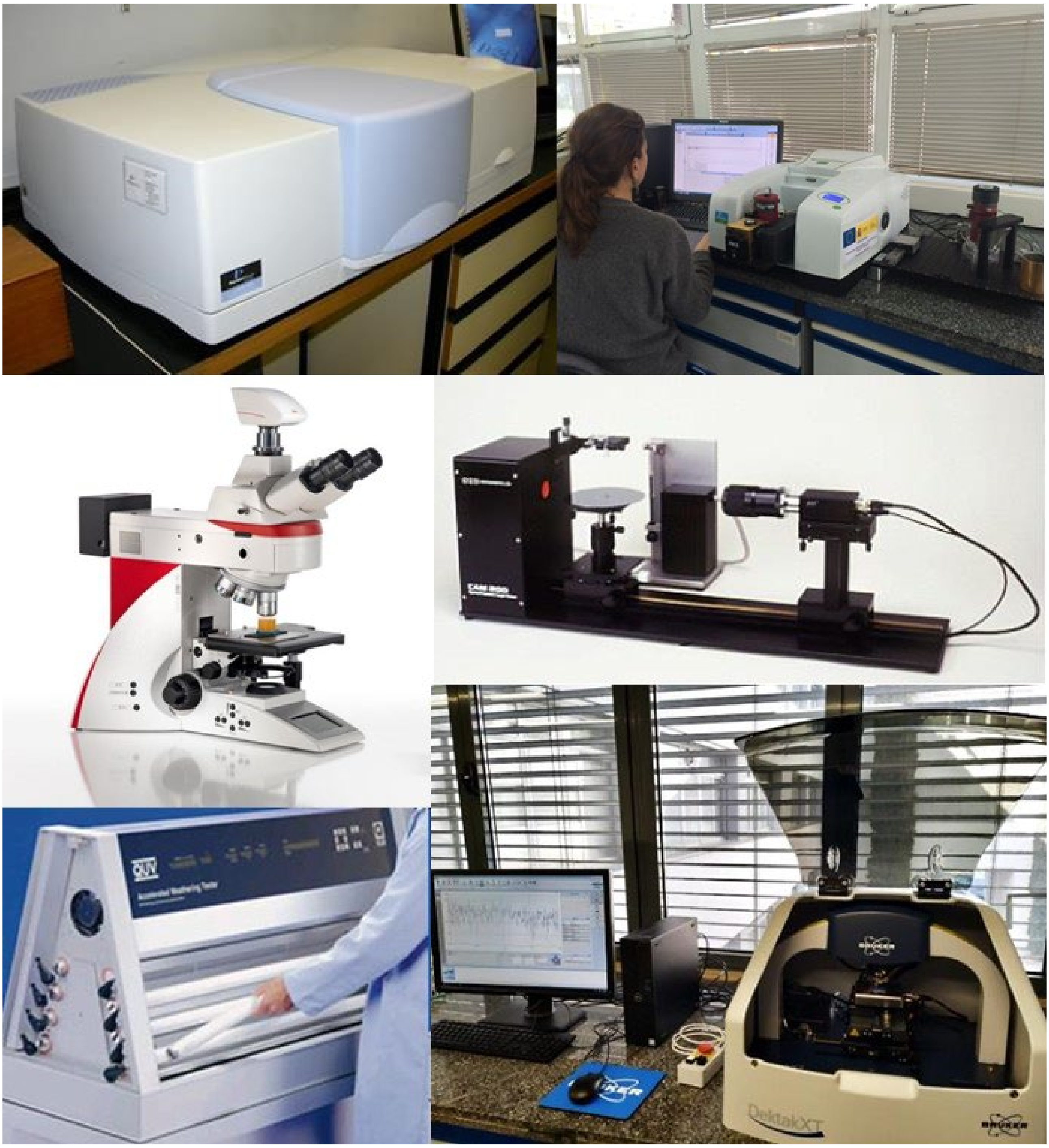


Figure 63. Advanced optical coatings laboratories equipment.

3.7 Porous media laboratory for solar concentrating systems - POMELAB

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

1) Thermal characterization of volumetric absorbers

Its main component is a test bench designed for the thermal test of new volumetric absorbers and configurations and its ageing in steady and dynamic conditions. The main components installed in this test bench (Figure 64) 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.

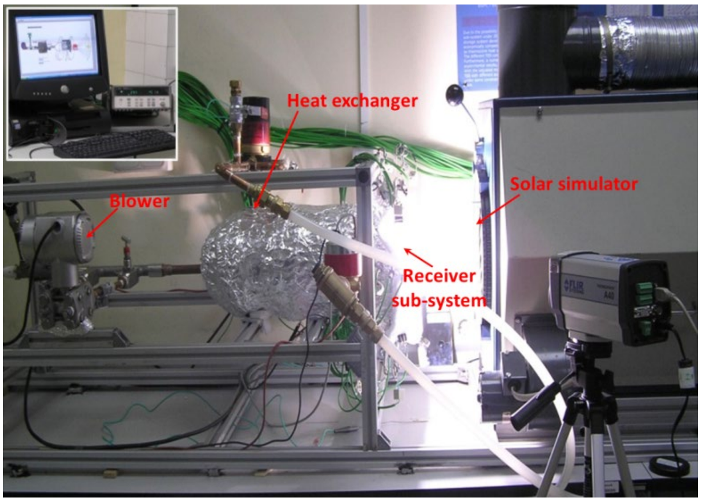


Figure 64. Test bench for volumetric receiver testing.

2) Thermal evaluation of porous beds in regenerative systems

Previous facility is complemented by an indoor facility to study thermal storage materials for high temperature using air as heat transfer fluid. This facility is composed of a thermocline storage test bench of about 0.1 m^3 as experimental loop for static and dynamic thermal characterization of porous beds. The system consists of:

- Six power heating resistor with a total power of 15,000 watts electric energy able to heat air up to a target temperature (maximum temperature limited by the resistor is 1,000°C) by means of a temperature controller.
- 35 K-type thermocouples units of 400 mm long are used to measure the material temperature. The behaviour of the tank is measured at 7 levels with 5 measurement each level.

- 35 T-type thermocouples units are used to measure the vessel outlet temperature in order to calculate thermal losses to the environment.
- The total power consumption is recorded, with a three-phase electrical measurement, to match the energy balances and the heat losses.

Moreover, the external surface temperature mapping is registered by a thermograph camera, which offers a complete image of the external chassis of the tank.

The two possible configurations of this test bench are (Figure 65):

- Static configuration: the experimental loop allows the characterization of effective thermo-physical parameters of the bed; material thermal conductivity, thermal losses, stored energy, etc. for different filler materials.
- Dynamic configuration: the experimental loop allows an agile characterization of the global storage at different working temperatures, filler materials, charges and discharges strategies, etc.

(a) (b)

Figure 65. Test bench for porous material characterization. Static configuration (a), dynamic configuration (b).

3) 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 66. Test bench for pressure difference measurement with configuration up to 300°C.

3.8 Laboratory for testing instrumentation and equipment for molten salt loops (BES-I and BES-II)

Molten salts are becoming not only a standard thermal storage medium, but also a working fluid for central receiver solar plants. However, there are still uncertainties about the durability of components and materials currently available on the market for molten salt circuits. Keeping this in mind, a specific activity line was implemented in ATYCOS Unit (Thermal Storage and Solar Fuels Unit). The equipment associated to this activity has been installed indoors at the PSA and it is composed of two test benches, BES-I and BES-II, especially designed and manufactured for the testing of valves, pressure transmitters and other molten salts components under real working conditions up to 600°C and 40 bar. Components with nominal diameters from 2” up to 6” can be evaluated in these test benches.

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.

3.9 Laboratory for the Assessment of Thermal Storage Materials

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

- HDR: Small furnace under ambient air atmosphere with an accurate control of heating/cooling rates, sample temperature monitoring; allows 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. 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 melting/freezing cycles up to 350°C, subsequent cycles, and cycles with stand-by periods for 10-20 g sample sizes.

Figure 67. Adjusting pressure at BES-II.

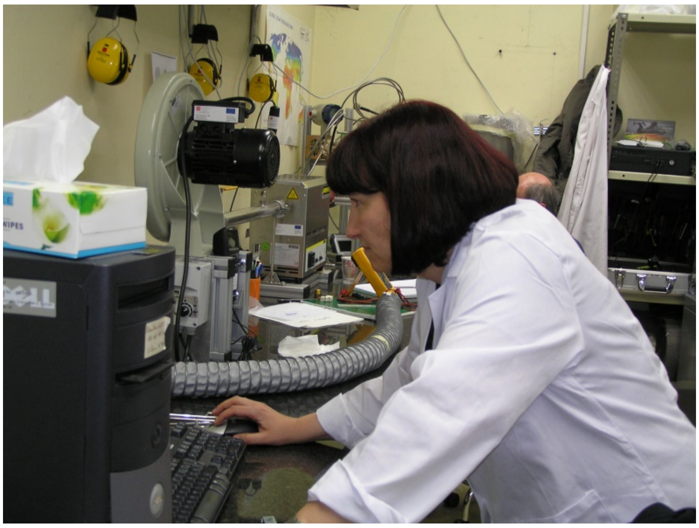


Figure 68. Working using the HDR device

3.10 Atmospheric Air Packed Bed Test Bench (ALTAYR)

ALTAYR 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.

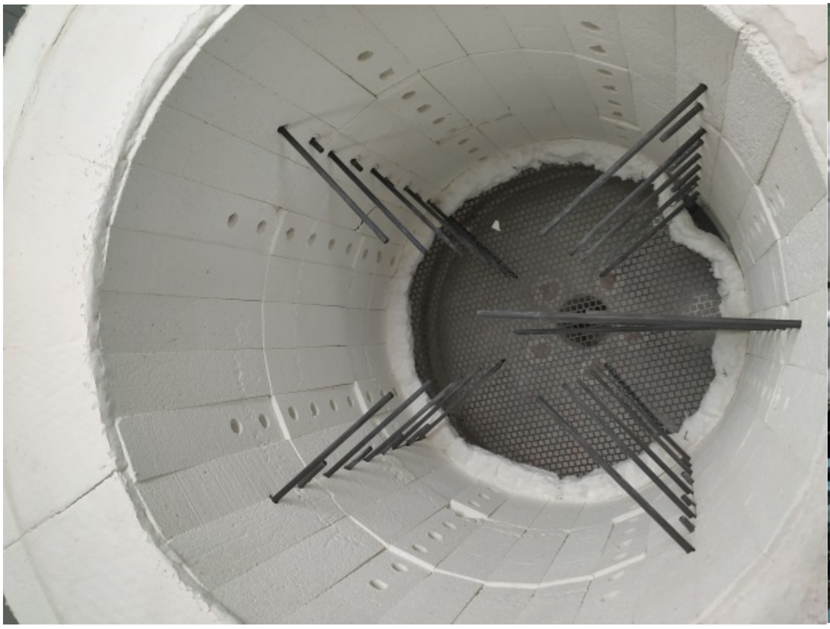


Figure 69. Picture taken from the uppest part of the tank, showing its internal room and thermocouples at different lengths and radial positions.

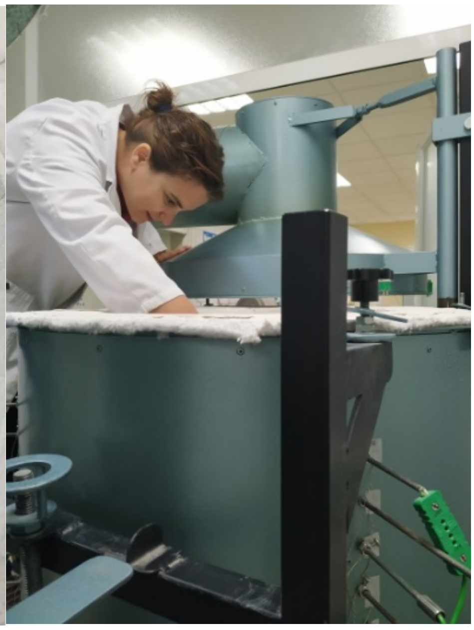


Figure 70. Researcher adjusting some items from the upper top of the tank.

3.11 PSA Water Technologies Laboratory - WATLAB

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

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

3.11.1 General laboratory

The main laboratory is 94 m^2 (Figure 71). 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 and conductivity-meter, and precision-scale table. In addition, it has a centralized gas distribution system, UPS, three-pin plugs connection and safety systems (extinguishers, shower, eyewash, etc.). The laboratory is also equipped with Vibrio fischeri and activated sludge respirometry toxicity measurement devices, biodegradability measurement by two respirometers for suspended activated sludge and for immobilized activated sludge, and equipment for the analysis of BOD and COD. Jar-Test system for the optimization of separation of solids for water treatment.

Figure 71. General view of the new PSA Water Technologies Lab.

3.11.2 Chromatography laboratory

This laboratory (Figure 72.b) is equipped with three high performance liquid chromatographs with diode array detector (HPLC-DAD and two UPLC-DAD) with quaternary pump and automatic injection; an Automatic Solid Phase Extraction (ASPEC) which permits working with low concentration of pollutants (Figure 72.c) and two ion chromatographs (Figure 72.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) analyzers by catalytic combustion at 670°C and total nitrogen (TN) analyzer with autosampler are also included. In addition, an AB SCIEX TripleTOF 5600+ was acquired to detect and identify non-targeted or unknown contaminants present in wastewater or generated (transformation products) during the water treatments: Triple TOF by a DuoSpray Source combining Turbo Ion Spray and APCI (Atmospheric Pressure Chemical Ionization) modes. Besides, the system includes metabolomics statistical package to analyze multiple samples from multiple experiments and identified possible chemical and biological markers (Figure 72.d).

(a) (b)

(c) (d)

Figure 72. 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.

3.11.3 Microbiology laboratory

47-m^2 microbiology laboratory with biosafety level 2 (Figure 73) is equipped with five microbiological laminar flow (class-II) cabinets, two autoclaves, three incubators, a fluorescence and phase contrast combination optical microscope with digital camera attachment. Besides, automatic grow media preparer and plaque filler and a filtration ramp with three positions are available.

Figure 73. General view of the microbiology lab at PSA facilities.

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

3.11.4 Microscopy laboratory

The microscopy laboratory is 11 m^2 room (Figure 74.a). A Scanning Electron Microscope (SEM) is located in this room. For the preparation of microbiological samples and catalysts to be analyzed in the SEM, the system is completed with a metal coater and critical point dryer. In this room it is also located two optical microscopes: i) A fluorescence and phase contrast combination optical microscope and ii) FISH microscope (Leyca) with fluorescence module to develop the FISH (Fluorescent in situ hybridation) technique for visualization of DNA hibrydation with specific probes in live cells used for monitoring of key microorganisms within a heterogeneous population (Figure 74.b). In addition, the system is completed by a station for photographic documentation, consisted in UV-trans-illuminator to detect and visualize DNA, RNA and proteins. It also includes a documentation station with a camera to take images of DNA, RNA and proteins.

(a)

(b)

Figure 74. a) SEM (Scanning Electron Microscope). b) Optical microscope for FISH technique

4 Solar Concentrating Systems Unit

4.1 Introduction

The aim of the activities carried out by the Solar Concentrating Systems Unit (USSC) is to promote and develop concentrating solar thermal (CST) systems for both power generation and industrial process heat, whether for medium/high temperatures or high photon fluxes. This PSA Unit is composed by two R&D Groups:

- Medium Concentration (MC) Group
- High Concentration (HC) Group

The MC group mainly works in the development of line-focus solar collector technology (parabolic troughs and linear Fresnel systems) and the HC group is focused in the development of point-focus technology, for solar tower systems, parabolic dishes or even the development and application of solar furnaces. Regardless of whether each group has its activities focused on a type of concentrating solar thermal technology, there are cross-cutting activities, common to both groups, related to the development and evaluation of optical concentrators (support/sun-tracking structures, reflectors), development of optical coatings for solar components (absorber, glass covers), durability analysis, etc. These horizontal activities are carried out by the USCS staff in the framework of research project of the Unit but also in projects involving other research units of the PSA.

A great effort also continued to dissemination activities, through participation in national and international conferences, workshops, seminars and Master courses to promote the knowledge about concentrating solar thermal energy technologies and their applications in general, new research on the topic and existing gaps that still exist to increase the commercial penetration of this energy technology.

4.2 Projects

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

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

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

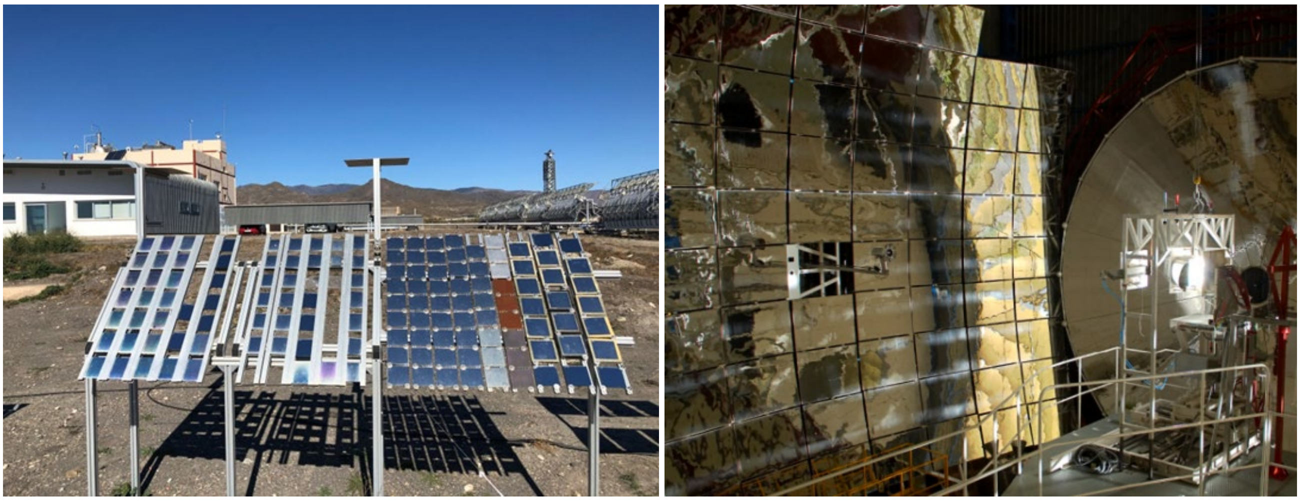
Funding agency: EU-H2020- NMP-16-2015.

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

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

Achievements in 2019: During the fourth year of the project, CIEMAT's activities related to the durability analysis of primary reflector coatings (front anti-soiling (AS) coatings and back-side (BS) paints) were continued. At least one sample of each of the 17 reflector types exposed in 11 worldwide sites were collected to be analysed in the laboratory (Figure 75.a). The main degradation mechanisms which affect to the durability of the reflectors were identified, being the most important: corrosion, UV radiation and erosion. A series of accelerated aging tests were carried out to determine which test is the most suitable to reproduce each degradation mechanism. Cooper accelerated salt spray (CASS) test was chosen as the best alternative to simulate the outdoor corrosion. Primary mirrors were tested in CASS test for 2,000 h and every 120 h the samples were properly assessed by optical analysis. Regarding UV radiation, it was demonstrated that the chambers with fluorescent lamp simulate better the outdoor behaviour than the chambers with a xenon-arc lamp. Finally, sandstorm test was performed to replicate the erosion. In addition, the research of the performance of 5 new AS coatings was done to evaluate their behaviour in outdoor exposure.

An improved secondary mirror was provided by Fraunhofer. This new material was tested both in aging tests and in real operating conditions. As this component will operate at higher temperatures (around 380°C), the secondary mirror was tested around the target temperature for 2,000 h in a muffle furnace. Also, the possible degradations which could take place overnight and provoked by thermal stresses (star-up and shut down of the plant and clouds) were simulated by a damp-heat test and a cyclic test where the samples suffered temperature shocks from ambient to the target temperature. The reliability of these aging tests was checked at the solar furnace SF-60 at the PSA (Figure 75.b) where the real operating conditions were achieved. The secondary mirror was tested for 150 h at 380°C.



(a) (b)

Figure 75. Test bench exposed outdoor at the PSA (a) and real operating test for secondary mirrors at the PSA solar furnace (b).

Optical properties of CIEMAT's selective absorber have been improved, adding an infrared reflector on the stainless-steel substrate. Solar absorptance is 0.955 in both absorbers and thermal is reduced from 0.13 on stainless steel substrate to 0.08 in chromium coated stainless steel. Thermal durability of both materials is being studied and after fifteen months at 400°C there is not any degradation in optical properties. Also, precursor solution developed at CIEMAT, to prepare antireflective coatings for glass covers of solar receivers, has been optimized and solar transmittance is higher than 0.97 and mechanical properties of the coating have been improved resulting in a higher resistance to abrasion-erosion degradation.

Finally, in relation to the dissemination activities (coordinated by CIEMAT), in this third year a workshop was organised and hold on 21st of November 2019 at Vallourec Deutschland GmbH in Düsseldorf-Rath (Germany) with the participation of 75 attendees. In addition, we have joined the consortium of H2020 projects dealing with Concentrated Solar Power technologies, an initiative of the European Commission, and we have participated in the H2020 Projects News on Concentrated Solar Power, a newsletter that was issued in April and November 2020.

Soluciones termosolares para integración en procesos industriales, SOLTERMIN

Participants: CIEMAT

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Angel Morales, angel.morales@ciemat.es

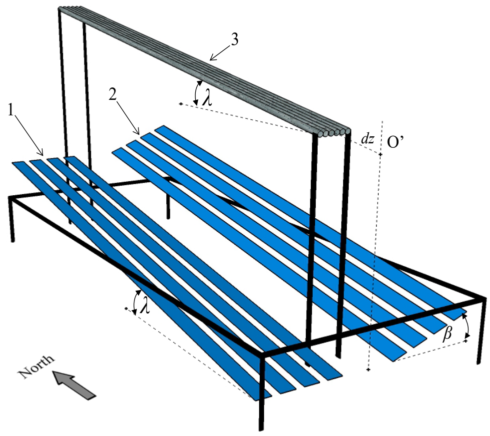
Funding agency: MINECO -Retos Investigación 2017: Proyectos I+D+i (Ref. ENE2017-83973-R) (Jan 2018 – Dec 2021)

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

Objectives: The project SOLTERMIN is developed by the Solar Concentrating Systems Unit and the Desalination Unit of the PSA. The project aims to advance in the development of new components and solutions to facilitate the integration of concentrated solar thermal technologies as thermal energy provider in industrial processes, with the following objectives:

- Development of a linear Fresnel solar collector for its integration in industries, including the development of a light-weight and optimized primary concentrator design to reduce optical losses and the development of an absorber coating valid up to 400°C and stable in air.
- Research on solar components for tower systems devoted to industrial process applications, including innovative and optimized heliostat designs and volumetric air receivers.
- Study of the durability and reliability of solar reflectors installed in industrial environments.
- Integration of linear Fresnel solar systems in different industrial processes: a) from a food and drink industry; and b) multi-effect distillation (MED) plant with steam ejectors. And integration of a solar tower system coupled to a Brayton cycle and a MED plant.

Achievements in 2019: The construction of the first prototype of an innovative linear Fresnel collector (see Figure 76.a) has started, completing the construction of the support structure and primary concentrator, including the mirror facets that have been manufactured at PSA. In October 2019 preliminary tests were performed to check the concentrated heat flux achieved in the receiver plane (see Figure 76.b); results of these initial tests showed concentrated heat fluxes up to 8.7 kW/m^2, which is in accordance with simulation results. The development of a selective coating stable in air for medium temperature applications has been completed (absorptance>0.95 and emittance @ 350°C<0.10); the durability of the coating has been also checked since it was completed the testing in a muffle during 15 months and no degradation of the optical properties was observed. The development of selective and non-selective coatings for high temperature (700°C) applications is on-going. The solution for an anti-reflective (AR) coatings for quartz windows has been also improved; the solar transmittance has been increased up to 0.98, and now durability of the AR solution is under development. Finally, the development of simulation studies in TRNSYS and EES to analyse the performance of iLFC-solar fields integrated in industrial processes (from the food and beverage industries, and also with desalination systems) have also started this year.



(a)


(b)

Figure 76. Simplified skecth of an innovative linear Fresnel solar collector (iLFC) developed in the SOLTERMIN project (a) and first prototype of iLFC under construction during a flux measurement test (b).

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

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

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

Funding agency: CIEMAT

Background: Since Concentrating Solar Thermal (CST) systems are a relatively young technology, the CST sector is still experiencing a lack of standards. This lack of standards is a barrier for the development of the technology and the evaluation and qualification of components.

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

Achievements in 2019: Like in past years the PSA unit of Concentrating Solar Systems has contributed significantly to standardization activities at both international and national levels in 2019. This contribution has been channelled via the international standardization committees IEC/TC-117 and the Spanish sub-committee AEN/CTN206/SC117. At Spanish level, besides the coordination of the working Group WG1 of AEN/CTN206 SC117 until September 2019, we have contributed to the new Spanish standard UNE-EN IEC 62862-3-2:2019 "*Requisitos generales y métodos de ensayo para captadores cilindroparabólicos de gran tamaño*" ("General requirements and test methods for large-size parabolic-trough collectors"). This standard is a translation into Spanish of the international standard IEC 62862-3-2:2018.

Within the framework of the Spanish sub-committee AEN/CTN206/SC117 we have also participated in the working groups developing three new standards related to:

- Technical specifications for instrumentation
- Technical specifications and qualification of solar tracking systems
- Qualification of flexible connections for line-focus collectors

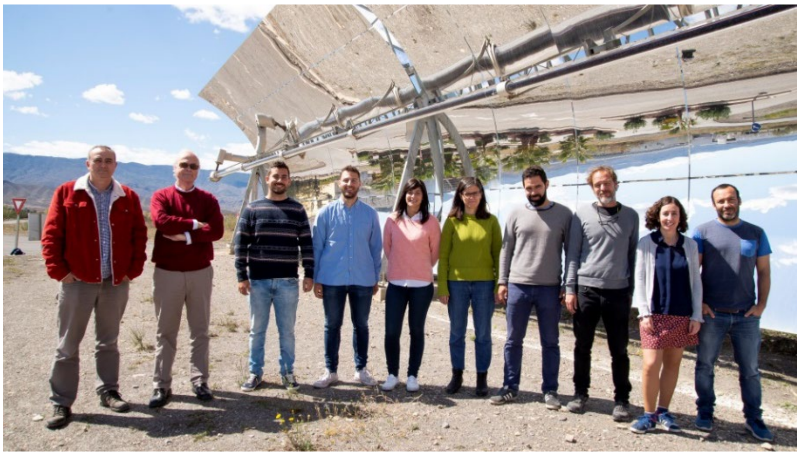
At international level, we have undertaken the Secretariat of the technical committee IEC/TC-117 in 2019 and we have also participated in the following IEC/TC117 project teams:

- PT 62862-3-3 "Solar thermal electric plants – Part 3-3: Systems and components – General requirements and test methods for solar receivers". Issued in 2019 as IEC TS 62862-3-3.
- PT 62862-2-1 "Solar thermal electric plants – Part 2-1: Thermal energy storage systems – Characterization of active, sensible systems for direct and indirect configurations".
- PT 62862-3-1 "Solar thermal electric plants – Part 3-1: General requirements for the design of parabolic trough solar thermal electric plants".
- PT 62862-4-1 "Solar thermal electric plants – Part 4-1: General requirements for the design of solar tower plants".
- PT 62862-5-2 "General requirements and test methods for large-size linear Fresnel collectors".

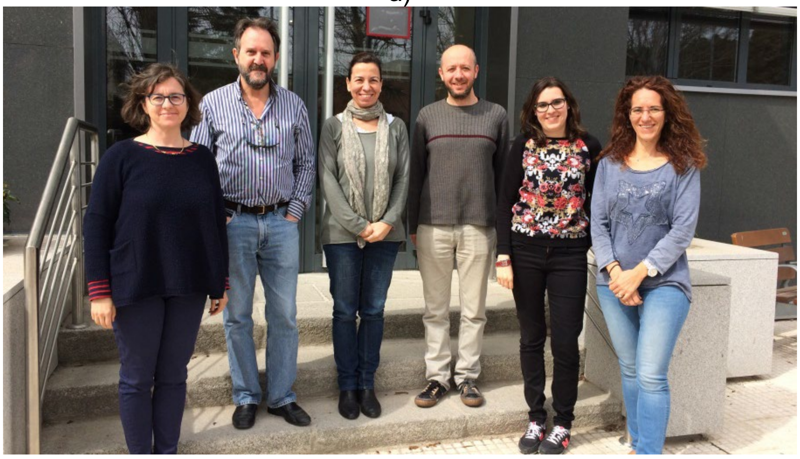
4.3 Medium Concentration Group

4.3.1 Introduction

The Medium Concentration group has continued its activities in the field of development, testing, and evaluation of components for line-focus solar collectors (SOLTERMIN and INSHIP projects and bilateral contracts with Spanish companies), testing of a new silicone fluid for parabolic troughs (SIMON project), modelling and simulation of power plants with parabolic-troughs using different heat transfer fluids (INSHIP projects), water saving technologies for power plants (WASCOP and SOLWARIS projects), testing of functional materials (RAISELIFE project), and contributing to the development of guidelines for the testing and evaluation of components for solar thermal power plants (Standardization activities, but also through Soiling and SHTF-Guideline projects financed by SolarPACES). The collaboration with the industry (manufacturing components or operating existing solar power plants) in the context of collaboration agreements or technical services has continued being noticeable.



a)



b)

Figure 77. Medium Concentration Group staff working a) at PSA in Tabernas (Almería) and b) at CIEMAT Headquarters in Madrid.

4.3.2 Projects

Water Saving for Solar Concentrating Power, WASCOP

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

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

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

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

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

Achievements in 2019: During the fourth and last year of the project, six test campaigns were performed at CIEMAT by the USCS, to assess the efficiency of several cleaning tools developed within

WASCOP project to reduce the water consumption in CSP plants. All the campaigns were performed in outdoor conditions and simulating the real operation of the plants during a whole year to cover the climate conditions of all the weather seasons. The results obtained constituted the main part of the cleaning activities within WP5 (coordinated by CIEMAT) and were used to validate the models developed within WP2, to develop the environmental and economic analysis within WP4. Following conclusions can be highlighted for each set of experiments:

- The soiling study performed with the samples of absorber tubes with a commercial anti-soiling coating showed that the soiling rate strongly depends on the inclination of the sample and the season, with an average decrease in the soiling rate of 3%. Also, the easy-to-clean behaviour was proved, with a cleanliness gain up to 4%.
- The analysis of the dust barriers (by Cranfield University) (see Figure 78.a) indicated that the natural barrier is not a suitable concept, while the artificial barriers contribute to the soiling reduction in a range between 1 and 3% under natural conditions at the PSA. If accelerated soiling condition is applied, the soiling reduction increases up to 40-50%. Also, it was found that the porosity is more important than shape of the barriers.
- The anti-soiling coatings for reflectors (by Rioglass and IK4-Tekniker) demonstrated to have easy-to-clean effect and a proper durability under outdoor conditions. The accumulated cleanliness gain was between 1 and 2.5 ppt, depending on the soiling conditions, with a maximum advantage of up to 7 ppt. The use of this coating might result in a reduction of the number of cleaning up to 12%.
- Ten low-cost soiling sensors (by IK4-Tekniker) were tested in two technologies, a heliostat field (the CESA one) and a parabolic-trough collector (the DISS loop). The soiling values were compared with the reflectance results from a portable specular reflectometer, achieving appropriate correlations under high soiling levels.
- According to the evaluation of the ultrosonic cleaning system (see Figure 78.b), it is able to reduce the water consumption 4 times average (7 times maximum), also proving its cleaning efficiency (higher than the conventional water spray system). The speed of the device is currently being optimized.
- Finally, some experiments were performed to optimize the traditional cleaning methods for absorber tubes of parabolic-trough collectors. For low soiling levels, without cementation, it was found that additives and/or hot water do not raise the cleanliness significantly.

(a)

(b)

Figure 78. Artificial dust barrier by Cranfield University (a) and ultrasonic cleaning system by IK4-Tekniker (b)

Solving Water Issues for CSP Plants, SOLWARIS

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

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Eduardo Zarza Moya, eduardo.zarza@psa.es

Funding agency: EU-H2020-LCE-11-2017.

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

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

Achievements in 2019: The main effort of the Solar Concentrating Technology Unit to SOLWARIS in 2019 was the design of the experimental campaign to be developed at La Africana solar thermal power plant to evaluate the prototypes of the water saving technologies developed in the project. The final version of the questionnaire and test plan and methodology prepared in 2018 for each of the technologies were elaborated in collaboration with the other partners and the corresponding deliverable documents including all the relevant information were successfully finished (i.e., confidential document D6.1 and public document D6.10). This information will be essential to avoid unforeseen problems during the implementation phase because potential problems will be identified well in advanced and proper solutions will be discussed and implemented. So, for instance, some problems related to the installation of dust barriers at La Africana were identified and proper solutions adopted late in 2019, thus avoiding a significant delay in the on-site evaluation at La Africana.

In addition, in order to assess the performance of the developed dry-cleaning technology for the heliostats of a solar tower power plant, artificial aging experiments were conducted in the laboratory under realistic and accelerated conditions. The cleaning principle is based on a brush performing a linear movement in vertical direction over the heliostat surface. The tests dealt with the degradation effects of the brush which is used for the cleaning. Especially the numerous “edge-kicking” processes were simulated under accelerated conditions and the resulting effects on the brush were described and quantified. Finally, the detailed plan for the five training courses to be given at PSA in 2021 was prepared in collaboration with the partners.

Silicone fluid maintenance and operation, SIMON

Participants: DLR (coordinator), CIEMAT, Wacker Chemie AG, TSK Flagsol Engineering GmbH, Senior Flexonics GmbH, TÜV NORD SysTec GmbH & Co. KG, Innogy SE, Rioglass Solar, S.A. Flucon Fluid Control GmbH, Ruhrpumpen GmbH.

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Funding agencies: Solar-ERA.NET Transnational Call CSP 4.3 2016; MINECO - *Retos 2017 Acciones de programación Conjunta Internacional* (Ref. PCIN-2017-009) (Oct 2017-Mar 2020); German Federal Ministry of Economy and Energy and German Federal Ministry of Innovations, Science and Research (Jan 2018-Apr 2020).

Background: Silicone based heat transfer fluids (SHTF) have been used in the past as heat transfer fluids in medium scale installations such as PTC test loops e.g. at PSA (Spain), NREL (USA) and elsewhere (DOW, Syltherm 800®). SHTFs are pumpable below 0°C, environmental-friendly, low in hydrogen formation, almost odourless and very low in acute toxicity. Until now, such fluids are not used in large-scale commercial CSP power plants because available SHTFs are currently far more expensive than the widely used eutectic mixture of diphenyl oxide and biphenyl (DPO/BP). The development, testing and demonstration of reliability, performance, and competitiveness of new SHTFs are of great interest of the CSP sector.

Objectives: The SIMON (Silicone fluid maintenance and operation) project is close related to the SITEF project (2016 and 2017) and has the objective to accelerate the market introduction of two HELISOL® products: HELISOL®5A and HELISOL®XA with improved viscosity properties, and associated parabolic troughs solar field's components (REPAs and receiver tubes) at temperatures up to 450°C. Such operation temperatures are beyond state of the art in PTC power plants and increase the overall power plant efficiency. This innovate project is based on a German-Spanish cooperation making use of the so called PROMETEO and REPA test facilities located at PSA.

Achievements in 2019: During this year, the testing to complete the proof of concept at 425°C of the heat transfer fluid HELISOL®XA, manufactured and supplied by Wacker Chemie AG, has continued at the PROMETEO pilot plant. In December the cumulated hours of operation with this heat transfer fluid were 1,110 h, where about 350 h correspond to operating hours with fluid temperature at the outlet of the solar field in the range of 425°C. Figure 79 corresponds to an exemplary operational graph with the main process variables during a typical test at 425°C. Besides this testing campaign,

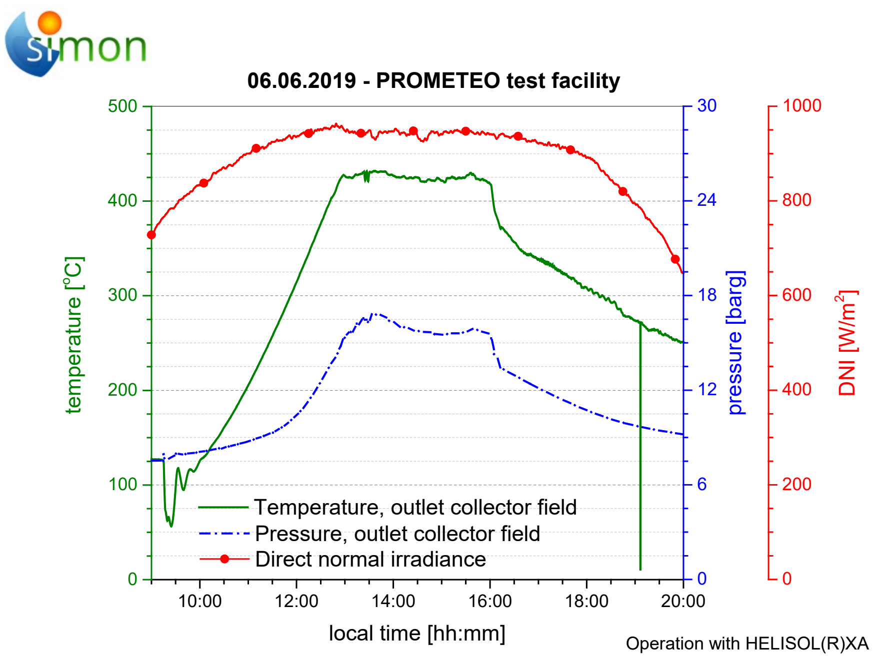

Figure 79. SIMON project: Experimental data during continuous operation of PROMETEO test facility with HELISOL® XA at 425°C.

in the REPA test facility it was completed the ageing of HELISOL®XA during 3,000 h at 450°C without any relevant incidence related to the use of the heat transfer fluid but some issues related to small leaks in the oil pump flanges that were solved. After finishing the ageing tests in REPA, a rotary and expansion assembly unit manufactured by Senior Flexonics was installed in the REPA test loop for a full life cycle test at T>430°C that is in execution.

Integrating National Research Agendas on Solar Heat for Industrial Processes, INSHIP

Participants: Fraunhofer (Coordinator), CIEMAT, AEE INTEC, FBK, UEVORA, CYI, CRES, ETHZ,CEA, METU, EERA.

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Mario Biencinto, mario.biencinto@ciemat.es

Funding agencies: H2020-LCE-2016-ERA.

Background: Worldwide 66% of heat is generated by fossil fuels and 45% of it is used in Industry as Process Heat. Despite process heat is recognized as the application with highest potential among solar heating and cooling applications, Solar Heat for Industrial Processes (SHIP) still presents a modest share of about 0.3% of total installed solar thermal capacity.

Objectives: The main objectives are grouped as:

- coordination objectives: a more effective and intense cooperation between EU research institutions.
- research objectives: to ensure efficient integration of existing Solar Thermal technologies into low and medium temperature processes, to develop technological solutions for high temperature processes and to foster an integration of SHIP in the overall energy system.

Achievements in 2019: The work of USSC of PSA-CIEMAT has continued in the following work packages:

- WP3 "Technology and applications to medium temperature SHIP (150°C to 400°C)
- WP5 "Hybrid energy systems and emerging process technologies"

During this year the work done by USSC in WP3 has been focused in contributing to the activities planed in Task 3.3 devoted to study soiling and corrosion of reflector materials in industrial environments and in Task 3.4 focused on developing and analysing compact and building envelope-integrated solar field concepts. CIEMAT has completed this year a contribution to DL 3.10 *Compact optical designs: simulated results for compact and/or building envelope embedded optical designs of line-focus concentrator technologies,* which is focused in characteristics and performance of the linear Fresnel collector under development in the national project SOLTERMIN. With regards WP5, CIEMAT has also completed deliverable D5.1.1d *Quasi-dynamic flexible model to simulate a solar field with PTCs and TESS for SHIP in TRSNYS,* focused in a simulation study on the annual energy performance of a parabolic-trough solar collector field integrated in a pasteurization process of a dairy factory located in Graz, Austria (see Figure 80).

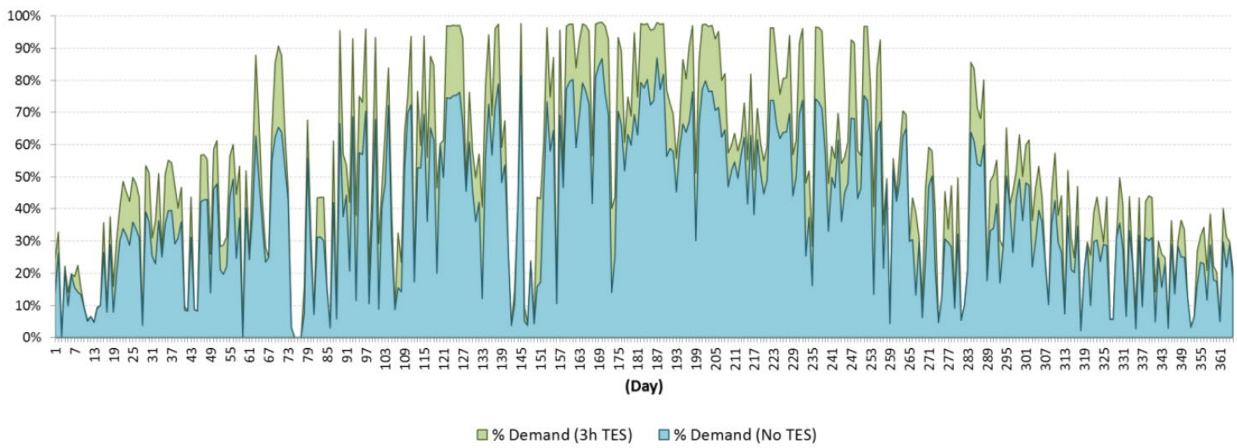

Figure 80. Daily thermal energy delivered by a PTC solar field to a pasteurization process (with 3h TES or with no TES), as percentage of the total demand, using meteorological data of PSA, Spain.

Silicone Based HTF in Parabolic Trough Applications – Preparation of a Guideline

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

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

Funding agency: SolarPACES (IEA).

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

Objectives: The project aims at forming an international expert work group with the assignment to elaborate an experienced-based guideline for the admission of silicone based HTF (SiHTF) in PTC applications. The guideline shall be the basis for future international standardization activities in the same field. The project duration is 18 months and comprises three main phases:

- Work package 1: Data compilation
- Work package 2: Admission procedure comparison
- Work package 3: Guideline document

Achievements in 2019: The project started in April 2019 with the activities included in WP1. This work package devoted to data compilation includes: the formation of the expert work group; a detailed summary of the qualification procedure execute for the silicon heat transfer fluid HELISOL® 5A, which is a fluid manufactured by Wacker Chemie AG and has been tested by CIEMAT and DLR in the SITEF project; and the compilation of standards and other existing documents applicable to the use of heat transfer fluids in solar thermal systems. Since CIEMAT has a wide experience in the preparation of standards for solar power plants, it has been the responsible lead and execute the compilation of main physical and chemical properties relevant for HTFs in hydraulic heating systems and standards and test methods available to measure or quantify these properties.

In the framework of WP2 and in collaboration with DLR, Wacker Chemie AG, and IEECAS, CIEMAT participated in the ellaboration of a detailed comparison of testing procedures available in ASTM, ISO, DIN, UNE and GB standards, and in defining which test methods are relevant for silicone based HTFs and which are not relevant due to the physical-chemical properties of this type of fluids compared to others as dyphenil oxide/byphenil mixtures that are extensively used in existing PTC solar power plants.

According to the work plan the first version of the guideline document will be submitted and available through the SolarPACES webpage in 2020.

Soiling measurements of solar reflectors

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

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Funding agency: SolarPACES (IEA).

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

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

Achievements in 2019: This project started in October 2019 and will last 18 months. The kick-off meeting was hold on November 2019 and the work to be done was organized as follow:

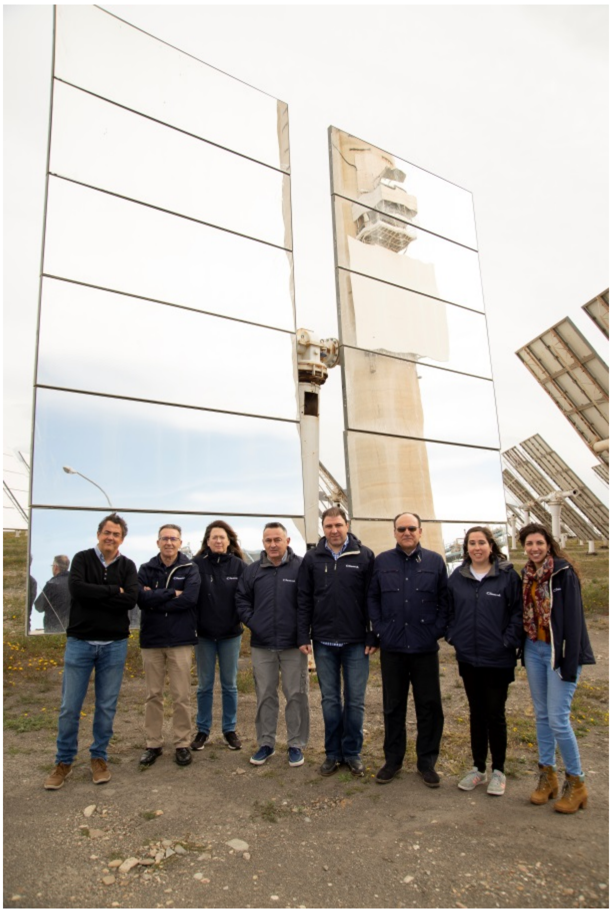
- Analysis of the field portable reflectometers. It will address a deep analysis of the main features of the field portable reflectometers. A document will be prepared comparing all the marketed instruments, based on the researchers knowledge, the available literature and several teleconferences that will be held with plant operators. Also, the main practical difficulties experienced by plant operators during the field measurements and the list of desired features for the ideal instrument will be addressed. In addition, data collected on previous experiments performed to compare field portable reflectometers will be analysed in detail to derive correlations that might help to align the different reflectometers' reflectance outputs.
- Correlation between portable and lab instruments. Soiled reflector samples will be measured both with portable equipment at certain λ, θ_i and φ and with laboratory equipment at a wider range of the parameters. The goal is to estimate conversion functions that will permit to derive more representative reflectance values from the experimental data acquired with simple field instruments. In particular, the correlation functions will include the estimation of the solar-weighted reflectance based on single λ measurements, for different dust types and particle loadings. In addition, the correlation functions will produce target values for different θ_i and φ, specific for any configuration of CSP technology, location, and receiver/reflector geometry.

4.4 High Concentration Group.

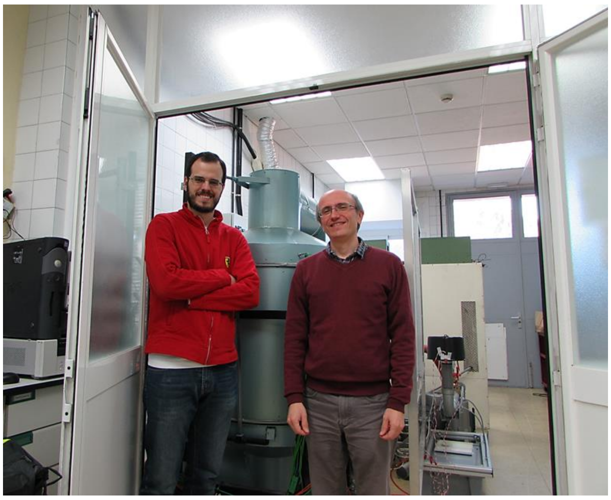
4.4.1 Introduction

In 2019, as in previous years, the activities of the high concentration solar group (HC) of the USCS have been focused on the firm commitment to volumetric receiver technology, with the aim of increasing the operating temperature of the central receiver systems beyond 600°C (which currently represents the commercial limit for solar tower technologies) with the idea of coupling these systems, not only to more efficient thermodynamic cycles (steam or gas power cycles), but also to industrial processes that require thermal energy at high temperature. In addition, as a consequence of this increase in temperature, research continues into materials that solve the problems associated with operation at high temperatures, in addition to implementing novel thermal energy storage through the use of liquid metals (Pb and Pb-Bi).

On the other hand, the experience acquired during these last years in the measurement of atmospheric attenuation of solar radiation has allowed us to open ways of collaboration with other countries and to export this technology to different areas with commercial CSP projects under development.



(a)



(b)

Figure 81. High Concentration Group Staff working at the PSA (a) and CIEMAT-Madrid (b).

4.4.2 Projects

Competitive Solar Power Towers, CAPTURE

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

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

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

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

Achievements in 2019: In 2019, all the project's efforts have been focused on the completion of the experimental installation of the CAPTURE project, which will be tested during 2020. This installation consists of a 300 kWth atmospheric volumetric receiver integrated with a new design of SiC porous absorbers. The receiver is coupled to 2 regenerators whose mission is to work as heat exchangers between hot atmospheric air and pressurized air at 10 bar, which is lately expanded in an 80 kW_e gas turbine. All the components, including the turbine, have been designed and developed ad-hoc during the previous 3 years of the project and, at last, they are all installed together to start generating experimental results. The commissioning of the system has been done during the last quarter of the year (see Figure 82).

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

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

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Antonio Ávila-Marín, antonio.avila@ciemat.es;
Inmaculada Cañadas, i.canadas@psa.es

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

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

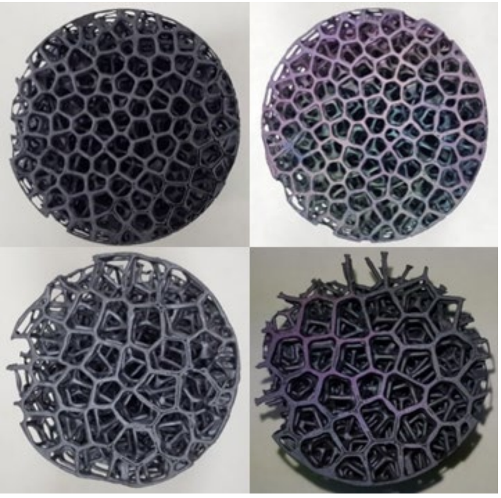
(a) (b)

Figure 82. Erection of the testing equipment of the CAPTURE project in the CRS solar tower facility at PSA (left) and first commissioning tests (left).

Objectives: NEXTOWER project aims at demonstrating high-performance durable materials for the next generation of concentrated solar power (CSP) air-based tower systems, making them commercially competitive in the energy market beyond 2020. While CSP towers are socially and technically appealing for their great environmental sustainability and the potential for electrical and thermal power generation, their industrial exploitation has been significantly slowed down by the materials used for the core component (i.e. the high temperature solar receiver) which is affected by limitations in the maximum working temperatures and in-service overall durability, mainly due to failure by thermal cycling.

NEXTOWER responds by taking a comprehensive conceptual and manufacturing approach that starts by optimizing for durability the ceramic materials to achieve 20-25 years of maintenance-free service receiver components, while increasing their operating temperature for thermodynamic efficiency at the system level and possible unprecedented applications downstream, such as the direct interfacing with a Brayton cycle or the supply of zero-emission heat for industrial/chemical processing. The actual exploitation of the hotter air (up to 800°C) is then crucially tied to the development of a high-temperature thermal storage, here inspired by nuclear fission GEN-IV technology and based on liquid lead by means of new corrosion resistant steels.

Achievements in 2019: CIEMAT is responsible for testing at a solar simulator the different innovative morphologies for open volumetric receiver technology. Besides the five geometries of absorbers based on simple unit cells, such as cube structure, diamond structure and tetrakaidecahedron cells, tested in 2018, two new geometries based on the Voronoi (V) morphology have been tested. Those two morphologies follow a constant (C) pattern and a graded (G) pattern. Moreover, both samples were tested with two different superficial treatments. Also, during this year, an optimized test bench for solar accelerated ageing of ceramics slabs at SF40 solar furnace has been developed (see Figure 83.b). Despite the difficulties encountered, the test bench is working properly, with high-speed cooling and heating rates (up to 30 seconds per minute on SiC slabs). And 10,000 ageing cycles have been carried out on ceramic samples and real concentrated solar radiation conditions. The later analysis of the slabs will determinate if the test bench configuration and operating conditions are adequate for NEXTOWER slabs requirements. Also, emittance at a high temperature has been estimated using a new method developed by CIEMAT using the new adiabatic test bench.



(a)

(b)

Figure 83. New absorber configurations tested at solar simulator (a) and testing facility for accelerated aging of the absorber samples (b).

Fortalecimiento de la calidad de sistemas solares industriales de torre mediante la medida de parámetros y estimación de la atenuación atmosférica con enfoque a entornos climáticos desérticos, 17BPE3-83761

Participants: University of Antofagasta (UA), Pontifical Catholic University of Chile (PUC), University of Chile (UCh), Fundación Fraunhofer Chile Research (Fraunhofer), Pontifical Catholic University of Chile (PUC), University of Chile (UCh), Plataforma Solar de Almería (CIEMAT), Photovoltaic Solar Energy Unit (CIEMAT), University of Almería (UAL), University of Huelva (UHU)

Contacts: Jesús Ballestrín, jesus.ballestrin@psa.es

Funding agency: Asociación Chilena De Energías Renovables (ACERA), Ministerio de Energía de Chile (MINEN), Corporación de Fomento de Chile (CORFO).

Background: Information about atmospheric attenuation of solar radiation between heliostats and receivers in Solar Tower Plants is necessary for their design, dimensioning and site selection. Said parameter also plays an important role in the operation of said plants, since it improves the estimation of the energy that reaches the receiver.

Objectives: Generation of the first map with estimated atmospheric attenuation values between heliostat and receiver for central receiver solar thermal tower power plants in the Atacama Desert in northern Chile.

Achievements in 2019: The project finished in June 2019. So far it resulted in the publication of 11 papers in first quartile scientific journals, as well as the presentation of 8 papers at international conferences and the organization of a forum on this topic at the Solar World Congress held in Santiago de Chile in 2019. The results of the map generated in the project indicate that the Atacama Desert is an ideal place for the installation of tower plants due to the operating conditions: maximum extinction values below 5% for 1km distance.

To generate the map, the methodology developed at the PSA was applied and 30 years of satellite data of 9 atmospheric parameters corrected with terrestrial measurements were analysed for the entire Chilean territory. The results of the data analysis have not only been essential for the elaboration of the map but are proving to be revealing in studies of other areas such as, e.g., studies for photovoltaic technologies performance.

Figure 84. Weather station at the *Plataforma Solar del Desierto de Atacama* (PSDA) in Antofagasta (Chile). It is equipped with a large variety of instruments ranging from atmospheric parameter measurements to solar resource measurements.

5 Thermal Storage and Solar Fuels Unit

5.1 Introduction

The Thermal Storage and Solar Fuels Unit (ATYCOS in its Spanish acronym) was formally launched in 2018 due to a reorganization of the former Concentrating Solar Systems Unit lead by Dr. E. Zarza. People of this former unit have been joined in ATYCOS to help turning concentrating solar thermal systems into a dispatchable technology by two R&D approaches: designing improved thermal energy storage systems and by producing hydrogen with thermochemical processes.

During 2019, ATYCOS researchers have been actively working in international, national, and local funded projects, already running -like POLYPHEM, WASCOP, INSHIP, ALCHEMIST-II and RESPACE- and other new ones -like ACES2030, E-CRETE and HYDROSOL-BEYOND. Apart from those, several technical services have been provided to companies, mainly dealing with testing and characterization of components and equipment for molten salt loops. On Thermal Storage a PhD has been defended and a new researcher has been incorporated thanks to the Talent Attraction Program of Madrid Community.

Through its experts, the Thermal Storage and Solar Fuels Unit participates actively in several scientific networks (Energy Storage JP of EERA, Task II and III of SolarPACES TCP of the IEA, task 58/33 SHC/ECES TCPs, Spanish association for Hydrogen -AeH2-) and national (AENOR-GT3) and international (IEC- CTN 206/SC 117/GT 03 and ASME-PCT52) standardization committees.

The activities on thermal storage deal with all aspects involved in the development, verification, and optimization of efficient Thermal Storage Systems (TESs):

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

Figure 85. Staff of ATYCOS working on Thermal Storage Group line in 2019

Solar Thermal Electricity (STE) is a very promising renewable source of energy but other applications have also been demonstrated, such as production of hydrogen and the integration of concentrated solar radiation into industrial processes.

The goal of our group addresses the demonstration, scale-up, of solar-driven thermochemical processes for the production of fuels (e.g. hydrogen, syngas) and industrial processes (e.g. cement, metallurgy, etc). The strategic task of the Group of Solar Hydrogen and solarisation of industrial processes exploit their know-how to develop suitable solar reactors and components and qualification of reactor materials to transfer the results to larger scales close to industrial size. A recent topic is the application of thermochemical processes in the space.

The lines of activity are concentrated in the following fields:

- Development of hybrid solar/fossil endothermic and thermochemical cycles processes for hydrogen production with concentrated solar energy.
- Technological feasibility of the use of solar thermal energy as the energy supply in high temperature industrial processes.
- Characterization of materials and components for solar reactors under extreme conditions.

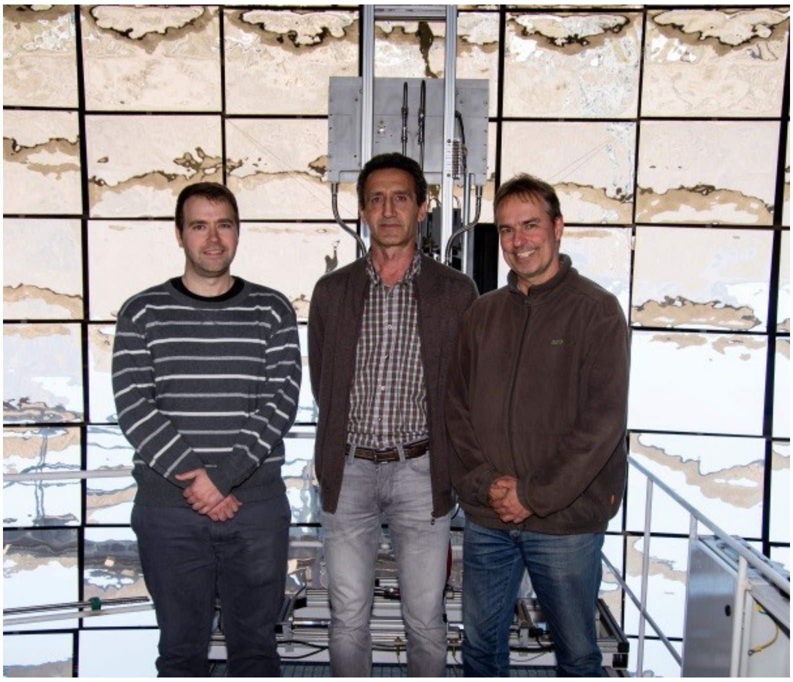


Figure 86. Staff of the Solar Fuels Group.

5.2 Projects

Small-Scale Solar Thermal Combined Cycle, POLYPHEM

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

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

Funding agency: H2020-LCE-2016-2017

Background: The technology consists of a solar-driven micro gas-turbine as top cycle and an ORC as bottom cycle. There is no water requirement for cooling. A thermal energy storage is integrated between both cycles. The resulting power block is a solar system able to meet a variable demand of power.

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

Achievements in 2019: The main contribution of CIEMAT is on the thermal storage system (TSS). ATYCOS coordinates the WP for the design and simulation of the TSS. This TSS is a thermocline tank with filler.

During 2019 the effective thermal conductivity of several samples with different concrete formulations has been measured in a special device already designed by ATYCOS. The protocols for looking at the compatibility of concrete samples and oil as HTF were established and the obtained experimental results evaluated. The integration scheme of the TSS in the whole Polyphem plant to be erected at Themis CNRS premises in France and the testing matrix for the storage system have been specified. The required instrumentation of the TSS at Themis have been defined. CIEMAT's model for the TSS thermohydraulic behaviour has been improved to take into account potential turbulences at the entrance and exit of the HTF to/out the thermocline tank.

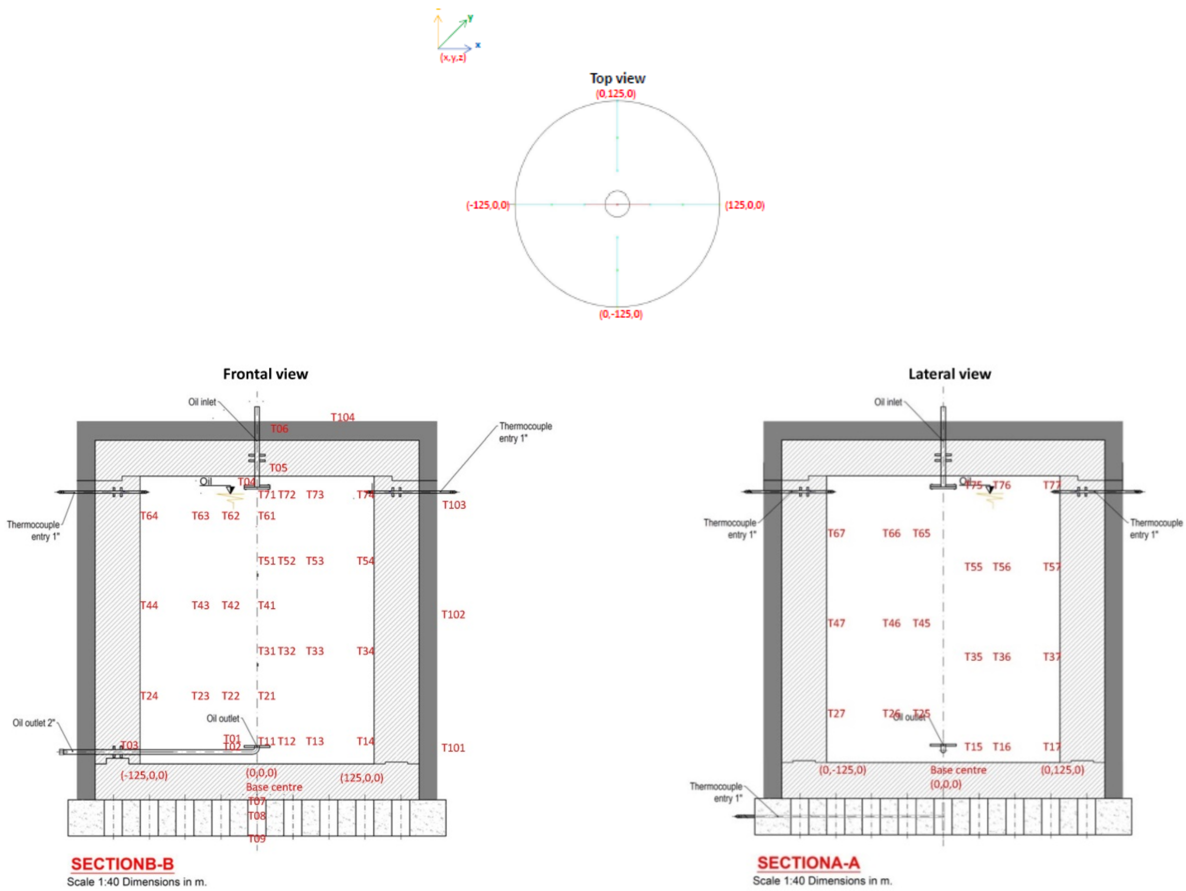


Figure 87. Thermal gauges assignment and location within the storage tank of Polyphem TSS.

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

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

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

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

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

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

Achievements in 2019: In relation to ATYCOS activities on Thermal Storage for ACES2030 two main activity lines can be distinguished: one focusses on defining the methodology to validate phase change materials as latent storage material and another one on packed bed thermal storage at high temperature with atmospheric air as heat transfer fluid.

In the first line, during 2019, several fatty acids have been sent to be measured with TGA at different heating rates and atmospheres in order to study their kinetic degradation, in principle, with models that can be found in the literature.

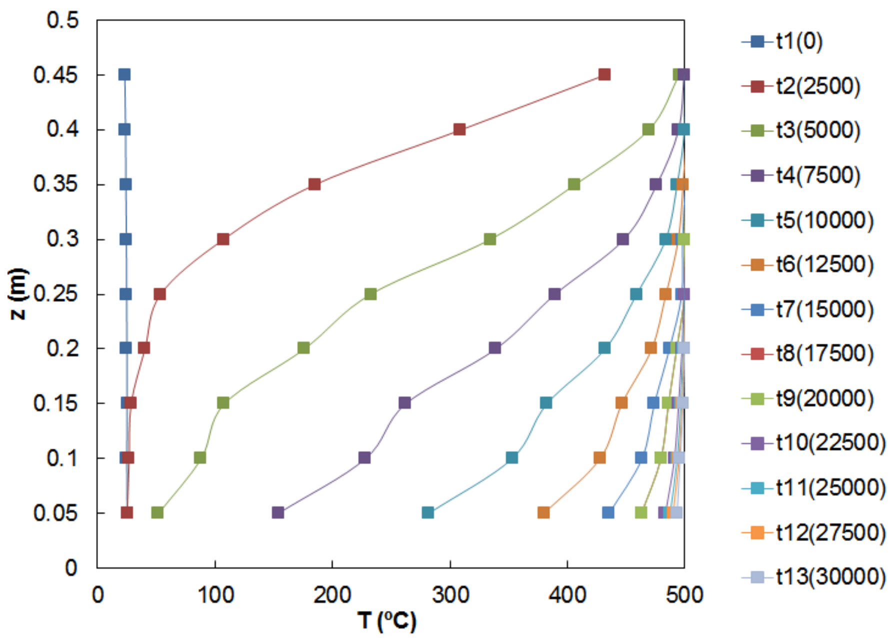


Figure 88. Measured temperature along ALTAYR tank length in a charge process.

In the second line, ALTAYR test bench have been used to test a commercial stone as filler at 300°C, 500°C and 700°C. Temperatures have been registered both in the air and inside some filler samples. It was observed that the side effects are so relevant that mask any temperature difference between the solid filler and the air HTF.

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

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

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

Funding agency: H2020-JTI-FCH-2018-1

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

Objectives: The main objectives of the project are summarized above:

- Improvement of the stability, cyclability and performance of the redox materials and redox structures (1,000 cycles or 5,000 hours of operation),
- Design novel solutions for high temperature solid-solid and solid-gas heat recovery. Heat recovery rates substantially higher than 50% are requested to meet that target,
- Embed and validate smart solutions to minimize the consumption of auxiliaries like flushing gas. Target should be to reduce energy losses through such auxiliaries to less than 25% of the energy output,
- Design and development of intelligent systems and a smart process of control and automation, including predictive and self-learning tools, and
- Demonstration of long-term performance of materials and key components under realistic boundary conditions using existing solar test facilities is needed. (core components like the solar receiver in a scale of about 500 kW). Testing period of the hardware, minimum 6 months.

Achievements in 2019: During 2019, the pilot plant was commissioned to complete the testing campaign already committed. The HYDROSOL-Plant is completed and ready for operation. Special emphasis will be put on the temperature level achieved, on potential temperature gradients, and on the active volume of the absorbers. The temperature distribution can be controlled by defining several aiming points on the receiver surface and adjusting the heliostats accordingly [1].

The core of this evaluation will be the quantitative assessment of the campaigns vs. the objectives set and current state-of-the-art figures according to the proposal goals: reactor efficiency (thermal and chemical), hydrogen Production Rate 1,400°C:≥ 3 kg/week, etc.

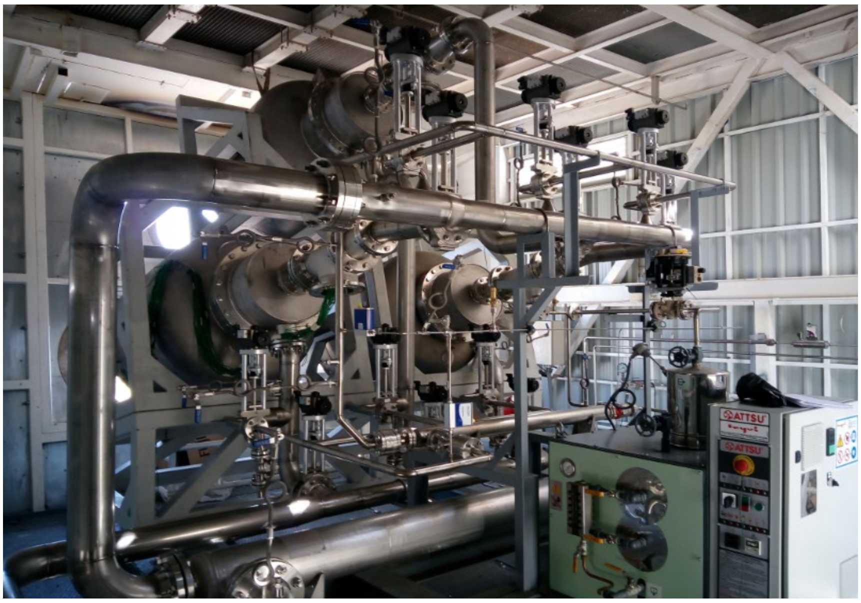


Figure 89. Photograph of the final configuration.

CSP in the transport sector and in the energy sector heat and power generation (ACES2030)

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

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Funding agency: Community of Madrid.

Background: The new challenges regarding emissions abatement in preparation for the National Integrated Plan on Energy and Climate imply a twofold increment of renewable energy penetration with the aim to reach 32% contribution in the energy mix (end use energy) in the horizon of the year 2030. This new objective involves a great effort to intensify the electrification of the energy economy, but also moves the energy system forward with a twofold increment in the use of renewable heat in industrial processes and five times increment in the penetration in transport sector. The R&D program ACES2030 on concentrating solar thermal power assumes that new priorities for CSP and relies on important outcomes obtained during the previous programmes SOLGEMAC, S2009/ENE1617 and ALCCONES, S2013MAE2985.

Objectives: ACES2030 focuses its R&D objectives onto three main challenges covering aggressive penetration of CSP within end use energy mix by 2030:

- Objective 1: Renewable electricity.
- Objective 2: Solar process heat. This objective is aligned with the integrated EC project INSHIP (Integrating National Research Agendas on Solar Heat for Industrial Processes) with

the ultimate goal to prepare an ECRIA (European Common Research and Innovation Agenda) on this subject.

- Objective 3: Solar fuels for transport.

Within objective 3, is exploring new materials, technologies, and processes for the production of H_2 and other alternative solar fuels for transport. This objective is fertilized by the realization in Móstoles of the pioneer EC Sunlight to Liquid Project and by other EU projects promoting the use of solar driven thermochemical processes, within the priorities of the SET Plan and the Fuel Cell and Hydrogen FCH 2 JU programme.

Achievements in 2019: Within objective 3, our research efforts were directed towards preparation and synthesis of the perovskites materials in the laboratory, improving the kinetics and reducing the working temperatures. This work has been initiated at the end of this year.

Multidisciplinary analysis of indirectly-heated particles receivers/reactors for solar applications in extreme conditions (ARROPAR-CEX). Subproject 3. Methodology and characterization of materials and components for receivers for solar applications under extreme conditions (RESPACE).

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

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

Funding agency: Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad, en el marco del Plan estatal de Investigación Científica y Técnica y de Innovación 2013-2016. Ref. ENE2015-71254-C3-2-R.

Background: Thermochemical processes require thermally and chemically stable reactor wall materials, which can withstand severe operating conditions suitable for specific solar fuels production. Reactor materials of construction comprising walls, the cavity lining, insulation, and shell need to fulfill the thermal and chemical requirements of severe operating conditions at high temperatures and under high-flux solar radiation. The research program ARROPAR-CEX proposes a multidisciplinary analysis on novel concepts of indirectly heated receivers/particle reactors for solar applications under extreme conditions. CIEMAT will study new multifunctional ceramic materials for solar applications under extreme conditions, focusing on the development of ceramic components that are adapted to operating conditions beyond the current state-of-the-art.

Achievements in 2019: The main objective during this year has been to establish a procedural methodology that leads to the reliable qualification of materials, components, and solar reactors, and which thus ensures their reliability and durability under extremely demanding operating conditions. This methodology will be validated in real operating conditions of solar radiation by employing Solar Furnace facilities.

A previous selection of materials was carried out, and AlN, SiC, ZrO_2-Al_2O_3 (KFSZ), Al_2O_3 (KATZ) materials were selected for these tests. These materials were subjected to thermal treatment to determine the optimal material for each specific application.

During 2019, two different thermal cycling procedures have been defined to depict degradation of the selected ceramic materials under specified operation conditions similar to those foreseen in present-day solar chemical reactors: service-condition tests and accelerated ageing tests.

A solar furnace has been used to expose the samples to thermal shock. Samples were subjected to thermal shock by receiving concentrated solar radiation during a number of heating / cooling cycles at SF40 solar furnace (see test set-up at Figure 90). Samples were submitted to 80 thermal cycles, ranging between 1,100 - 1,400°C. Dwelling phases were set at 90”, both at low and at high temperatures.

For diagnostic purposes, weight loss, visual inspection, hemispherical reflectance, and phase composition (through XRD) of the samples were selected as main parameters. Our findings indicate that KATZ has proven to be very stable under the experimental test methodology proposed in all the parameters taken into consideration and a potential candidate as a structural material for these processes.

Figure 90. Sample under solar exposure at the SF40 facility.

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

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

Contacts: Thorsten Denk; tdenk@psa.es

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

Background: Every three years, the ESA Council on Ministerial Level meets to decide about the European activities in space for the coming years. The latest meeting was end of November 2019 in Sevilla (Spain). The European Space Agency (ESA) planned to propose to the Council (among many others) a mission with the purpose of demonstrating In-Situ Resource Utilization (ISRU) on the Moon. ISRU means that *local* resources, especially minerals, are used to produce useful goods like air (oxygen), water, metals, construction materials, or rocket propellant. To prepare the proposal, ESA issued several ITTs (Invitations to Tender) to do detailed preparatory studies about the mission, divided into the segments transportation, communication, and payload, this project is among them. It is the follow-up project of the Alchemist-project (ESA-Contract ITT AO-9107) carried out in 2018.

In the years before, at the PSA, there was designed, built, and tested in the Oresol project a full-scale test plant able to reduce ilmenite (a common mineral on the Moon) with the help of hydrogen and concentrated solar power to produce water. The knowledge and practical experience gained in Oresol was the decisive advantage of PSA to be invited to participate in the ITT.

The project ALCHEMIST is the first ESA payload study that defines the high-level details of a lunar ISRU payload operating with the hydrogen reduction process.

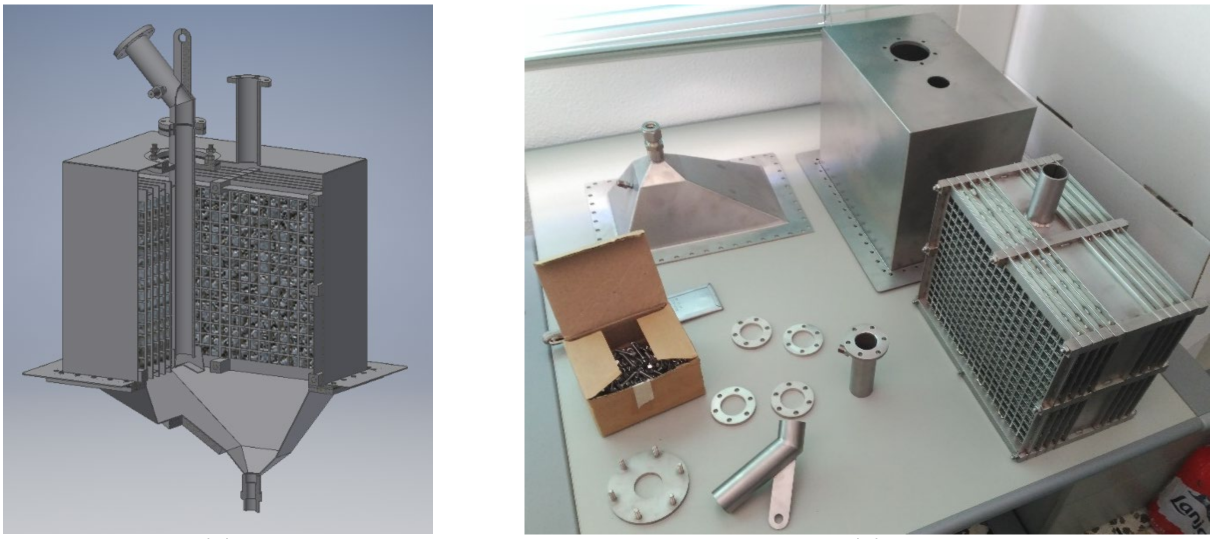
Objectives: The principal goal of the phase was to define the hardware of a hydrogen reduction plant operating on the Moon. This included the sub-systems for excavation of the lunar sand (regolith), the pre-processing like sieving or enrichment, the processing of the regolith with hydrogen at 900°C,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

Achievements in 2019: In 2019, the Alchemist/ALPHA study was carried out like requested by ESA. The design of the reactor was the responsibility of PSA. First, basic values like gas velocity, gas flow, reactor geometry (diameter, height), residence time, and power requirements were estimated, calculated, and determined. Of special importance is the gas velocity in the reactor. This value is difficult to obtain, because besides the usual parameters like size, sphericity, porosity, and density of the particles, and density and viscosity of the gas (determined by gas composition and temperature), the gravity plays a crucial role. As on the Moon it is only 1/6th of Earth's value, there is very few experimental data available. This required a design with a large margin for the main gas flow parameter. After that, the reactor was designed in certain detail (Figure 91). It includes the inlet for the fresh (top) and the outlet for the spent (bottom) particles, as well as the gas distributor (the circular feature at the bottom), the reaction zone (below the cross), the so-called freeboard (the "splash-zone" above the fluidized bed), and the gas outlet via two filters made of sintered metal (the two large cylinders in the upper part). The thermal power is supplied by an electrical heater wrapped around the fluidized bed zone (not drawn in Figure 92.a). The whole reactor must be well insulated to minimize energy losses.

Figure 91. CAD model of the lunar test reactor.

Furthermore, in 2019, the test campaign with the Oresol reactor was continued, although only at a very low pace. The main objective of the tests was to increase the proportion of hydrogen in the feed gas (due to safety reasons, the feed gas is mainly argon) to obtain useful data for the Alchemist study and to demonstrate the production of 100 g water in one single test. Very good weather conditions allowed for testing on four subsequent days in January. Nearly complete conversion of the hydrogen gas (mix: 8% H_2, 92% Ar) was achieved, but the problems with the filter clogging could not be overcome.

To solve these problems, a new filter was designed (Figure 92.b). Despite of severe volume restrictions (it had to fit into the same place as the old filter), it was possible to increase the filter area by a factor of twenty. This was achieved by massive parallel arrangement of the filter cloths.



(a) (b)

Figure 92. New filter for the Oresol plant

A second test campaign was scheduled for two weeks end of September / beginning of October. Unfortunately, the new filter was not yet available at this time, because administrative obstacles delayed the purchase for several months. The tests had to be done once more with the old filter, and again they were not successful. As a result, no further useful data could be obtained for the Alchemist/ALPHA study.

6 Solar Desalination Unit

6.1 Introduction

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

Main current research lines are the following:

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

During 2019, the UDeS has continued with its relevant activity in the field of thermal water separation processes using solar energy. Alternative applications of thermal technologies like MED and MD in the regeneration stage of closed-loop salinity-gradient power generation processes and industrial wastewater treatment were demonstrated at pilot scale level within RED-HtP and REWACEM H2020 projects. A new facility for the research of innovative cooling technologies in CSP plants has been incorporated into the portfolio of its experimental facilities.

Figure 93. Members of the UDeS Unit.

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

- Member of the European Desalination Society (EDS) Board of Directors (2016-2019)
- Coordination of the Renewable Energy and Desalination Working Group of the European Water Platform (WssTP)
- Coordination of the Renewable Energy Desalination Action Group of the European Innovation Partnership on Water of the European Commission.
- Operating Agent of SolarPACES (Solar Power and Chemical Energy Systems) Task VI (Solar Energy and Water Processes and Applications).

During the year 2019, research activities were developed within the framework of projects covering both national and international activities with academic and industrial involvement.

6.2 Projects

Conversion of low-grade heat to power through closed-loop reverse electro-dialysis, RED-Heat-to-Power

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

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

Funding agency: European Commission, Horizon 2020 programme

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

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

Achievements in 2019: The activities of the RED Heat to Power Project ended this year with the pilot-scale demonstration in Tilburg (Netherlands) of a closed-loop salinity gradient power plant based on the reverse electrodialysis process. CIEMAT's participation during the project has focused on the investigation of the regeneration stage of the diluted saline solution resulting from the reverse electrodialysis process using low enthalpy (40 - 100°C) thermal separation processes such as multi-effect distillation (MED) and membrane distillation (MD). The results have shown that thermal to electrical conversion efficiencies of up to 10% can be reached by employing MED technology. However, due to the reduced scale of the plant, a membrane distillation system was chosen for the aforementioned demonstration plant An extraordinary progress in improving the efficiency of membrane distillation was achieved by using vacuum air-gap configuration in multi-envelope spiral-wound modules, decreasing the specific thermal energy consumption values to about 46 kWh/m^3.

Figure 94. Pilot-plant for assessment of combined reverse electrodialysis and membrane distillation.

Resource recovery from industrial wastewater by cutting edge membrane technologies, REWACEM

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

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Funding agency: European Commission, H2020 Programme

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

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

Achievements in 2019: During this year the activities of the REWACEM Project have concluded with the demonstration at pilot-scale of a plant combining diffusion dialysis, membrane distillation and reactive precipitation. This plant was installed in the factory of the company Electroníquel (Gijón, Spain) and recovery values for sulfuric acid (85-100%) and copper (85%) have been achieved, also obtaining high-quality permeates (50-60 µS/cm) from the residual water of the copper electroplating processes carried out in the aforementioned factory.

Solving water issues for CSP plants (SOLWARIS)

Participants: TSK (coordinator) (ES), CEA (FR), DLR (DE), CIEMAT (ES), CRANFIELD UNIVERSITY (UK), IK4-TEKNIKER (ES), RIOGLASS SOLAR (ES), INDETEC (ES), FENIKS (ES), BSC (ES), BRIGHTSOURCE (IL), AMIRES (CZ), BERTIN (FR)

Contacts: Patricia Palenzuela, patricia.palenzuela@psa.es

Funding agency: European Commission, H2020 Program

Background: The electricity production from concentrated solar thermal power (CSP) has to cope with two main challenges, the reduction of the water consumption since a high insolation often occurs in locations with a lack of water resources, and also the improvement of the cost-effectiveness of the CSP technology. Water at CSP plants is required for the following tasks: cleaning of the collector solar field, cooling the power block condenser in the case of a water-cooled steam turbine and to make-up water in the steam cycle.

Objectives: The overall purpose of the SOLWATT project is to upscale, implement and demonstrate cost-effective technologies and strategies that bring about a significant reduction of water of CSP plants while ensuring excellent performance of electrical power generation. The SOLWATT approach proposed will tackle all segments of water consumption in a CSP plant by:

- 90% for reduction of cleaning operations,
- 15 to 28% for cooling of turbine condenser, and
- 90% for recovery and recycling of water.

Then, a total reduction of water consumption by:

- 35% for a wet cooled CSP plant, and
- 90% for a dry cooled CSP plant.

Achievements in 2019: During this year, UDeS has been focused in the optimum design of a multi-effect evaporator (MEE) unit to be installed at a real CSP plant (La Africana CSP plant located in Córdoba, Spain), which will treat water from different points of the CSP plant to be recovered and re-introduced again in the CSP plant. The MEE unit is being manufactured by the Spanish company INDETEC. Also, the connection points for the integration of the MEE into La Africana have been decided after several visits to the CSP plant jointly with the partners TSK and INDETEC. Besides, UDeS together with the company INDETEC have decided the instruments and control loops of the MEE unit. Finally, the implementation of a dynamic modelling of the MEE unit in Modelica has been started by researchers of UdeS, basing on models published in the literature. This model will be calibrated once the MEE unit is under operation in La Africana. On the other hand, UdeS and USSC have been working in the elaboration of the schedule, teachers, topics, etc, of a series of knowledge and practice-oriented courses that will be held at PSA in the next years

Water Saving for Solar Concentrating Power, WASCOP

Participants: CEA (coordinator) (FR), DLR (DE), CIEMAT (ES), Cranfield University (UK), Fundación Tekniker (ES), MASEN (MA), Rioglass Solar (ES), Archimede Solar Energy (IT), OMT Solutions (NL), Hamon D´Hondt (FR), AMIRES (CZ).

Contacts: Patricia Palenzuela, patricia.palenzuela@psa.es

Funding agency: European Commission, H2020 Program.

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

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

Achievements in 2019: This project is jointly developed by the UDeS and the USSC. During 2019, UDeS has been in charge of the installation of a testing facility at PSA for the evaluation of a hybrid cooling system (composed of a Wet Cooling Tower and an Air-Cooled Heat Exchanger) and its comparison with conventional dry cooling systems (Air Cooled Condensers). The contract of two companies to do the engineering and mechanical assembly has been carried out. On the other hand, the electrical connections, SCADA system and instruments installation has been done by PSA staff. After the installation, the start-up was carried out and the facility was finally ready for testing in July 2019. An exhaustive test campaign at different hybrid cooling configurations (series and parallel and at different split ratios in the last case, 25%, 50% and 75%) and at different operation conditions (several ambient temperatures and several condensation powers) has been performed from July until December 2019 (when the project has finished) in order to find the best operational strategies in terms of water and electricity consumption. For the evaluation of the best operational strategies, two indexes that represent the specific water consumption (SWC) and the specific electric consumption (SEC) of the hybrid cooler, were proposed. Configurations that fulfil a SWC lower than a certain limit value and have the minimum SEC at the same time, were established as the best ones. Figure 95 shows results of these two indexes for different condensation power at an ambient temperature range from 16 to 27°C. From the results obtained in the test campaign performed, it was concluded that considering a limit value of SWC 0.7 L/h/kW$_{th}$ the best configuration in terms of water and electricity consumption is parallel 25%. Likewise, it was obtained that if the best configuration is used, successful results in terms of water and electric consumption reduction with respect to the only-dry and only-wet operation modes can be achieved, resulting in 52% and 64%, respectively, for the maximum condensation power (200-225 kW$_{th}$).

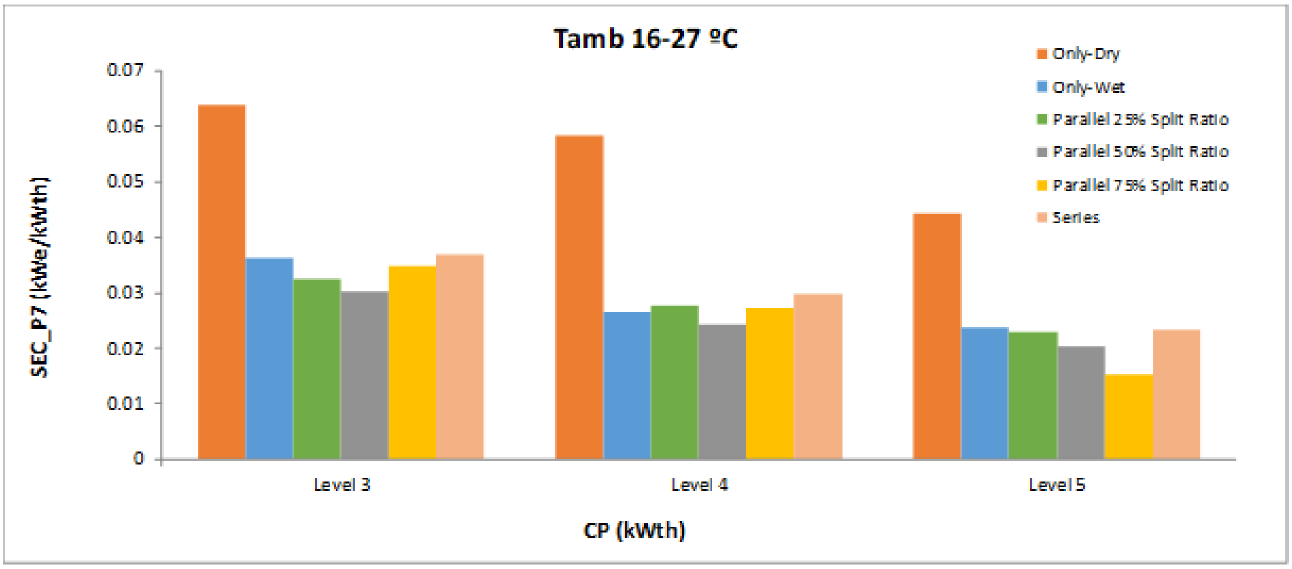
Bio-mimetic and phyto-technologies designed for low-cost purification and recycling of water, INDIA-H_2O

Participants: UOB (coordinator) (UK), PDPU (IN), CIEMAT (ES), AQP (DK), AQPA (SG), IHE (NL), LEITAT (ES), GBP (IN), MOD (UK), BGU (IL), DAV (IN), ACWADAM (IN), JU (IN), OPC (IN), CETIM (ES), AU (UK), CEERI (IN)

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

Funding agency: European Commission, H2020 Programme

Background: Water is an essential human need and over the next decade the number of people affected by severe water shortages is expected to increase fourfold. In the developing countries that are most affected, 80-90% of all diseases and 30% of all deaths result from poor drinking water quality. There is growing recognition by governments and corporations that future global prosperity is intimately tied to the availability of fresh and safe water. These challenges are acutely felt in India, where population growth, industrialisation and climate change exacerbate the crisis. Water quality, water shortage and accumulation of pollutants are threats which must be addressed to maintain sustainable development in both rural and urban areas across India and other emerging economies.



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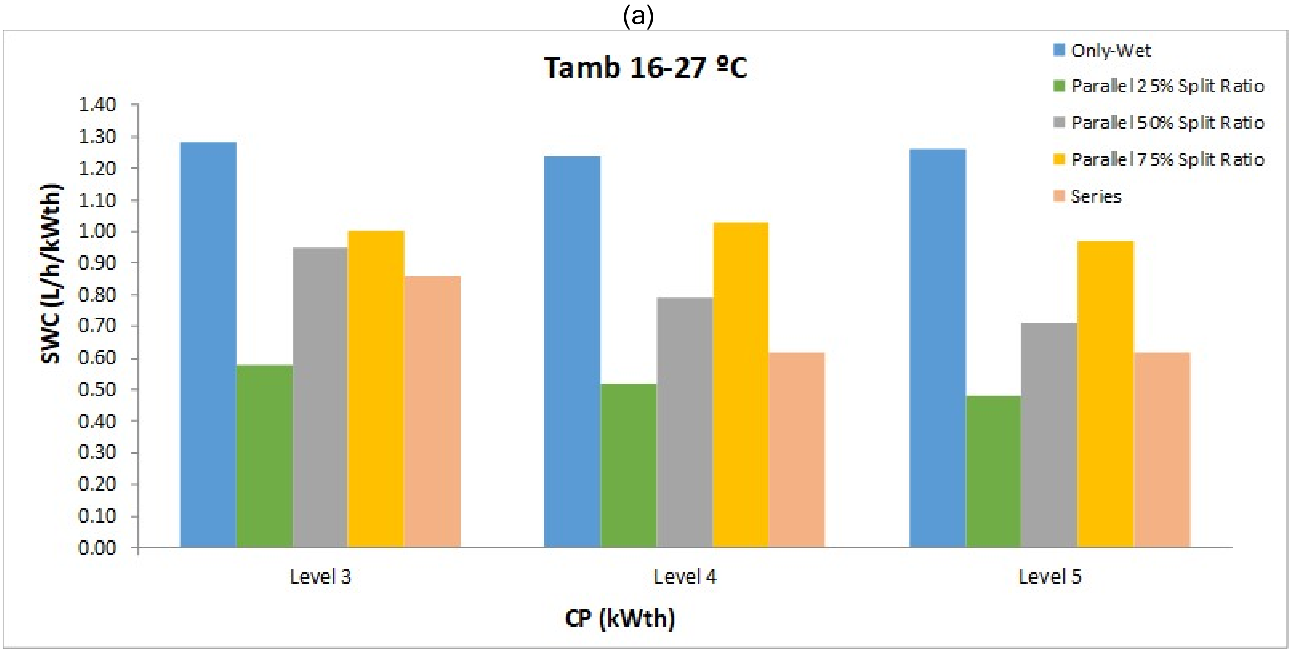

(b)

Figure 95. Results of SEC (a) and SWC (b) *vs* condensation power (CP) in the different hybrid cooler configurations. Level 3 corresponds to a condensation power between 120-125 kW_{th}, Level 4 corresponds to a condensation power between 170-175 kW_{th} and Level 5 corresponds to a condensation power between 200-225 kW_{th} (nominal conditions)

Objectives: The overall aim of INDIA-H_2O is to develop, design and demonstrate high-recovery low-cost water treatment systems for saline groundwater and for domestic and industrial wastewaters. The focus for developments will be in the arid state of Gujarat, where surface water resources are very scarce. Cost-effective technologies and systems are proposed with the aim of lowering energy costs through dramatic improvements in energy efficiency, new bio-based approaches to water recycling, and use of renewable energy. Reject waste streams will be minimised or reduced to zero, thus protecting the environment. Advanced membrane processes, including biomimetic FO and RO and layer-by-layer assembly of ultra/nano-filtration membranes, will be developed and combined to provide new methods of purifying water from saline groundwater and from municipal and industrial wastewaters, providing water that is safe for drinking or suitable for irrigation. They will be implemented in highly cost-effective modes and systems incorporating phytoremediation and complementary processes.

Achievements in 2019: Project activities have just started in 2019. The location for the main application was chosen: the village of Lodhva in Gujarat. CIEMAT has participated in the design of the solar-powered batch RO system to be implemented in the village.

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

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

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

Funding agency: European Commission, INTERREG Atlantic Area Programme

Background: According to the priorities established in the Research and Innovation Strategies for Smart Specialization (RIS3), sustainable solutions to technological advancement of the energy and water sectors with regard for regional specific features are required, from industrialized to rural. Technological solutions should be adapted to different scenarios commonly exist in the Atlantic Area, specially to coastal areas and islands. To this end, integrated planning of sustainability on energy production for the water cycle is needed.

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

Achievements in 2019: Project activities started in April 2019. CIEMAT will be devoted to solar energy related actions and to the experimental assessment (at pilot plant level) of power generation based on pressure retarded osmosis processes, plant retrofitting approaches and the use of industrial waste heat in membrane distillation applications. During 2019, modifications at FO-PRO bench scale test plant at PSA has been established to address project objectives. In addition, new membrane distillation modules with high energy-efficiency (GOR>13) have been tested at PSA powered by solar energy and empirical models for different temperatures and salinities have been validated.

7 Solar Treatment of Water Unit

7.1 Introduction

The main objective of the Research Unit of Solar Treatment of Water is the use of solar energy for promoting photochemical processes, mainly in water for treatment and purification applications but also for chemical synthesis and production of photo-fuels. Our knowledge about solar photochemical systems and processes at pilot and pre-industrial scale is backed by 25 years of research activity. The Unit was pioneer in Spanish and keeps a consolidated national leadership. The Unit has participated in more than 25 EU projects since 1997 mainly focused on the development of solar technologies for water treatment. The Facilities are extremely well equipped and are among the best in the world in the field of advanced oxidation processes (AOPs). We are also pioneers in the use of advanced analytical techniques for the evaluation of such processes. Formal collaborations in the academic sector include dozens of public institutions in the EU, South America and Africa. Industrial collaborations on recent projects include companies from Austria, Italy, Denmark, India, and many others in Spain.

In order to promote the higher education of young researchers in the environmental applications of AOPs, as well as to overcome national boundaries and bureaucratic barriers, a group of European scientists founded the “European PhD School on Advanced Oxidation Processes” in June 2014. Subsequently (October 18, 2018), with the aim to make the School international, Institutions from Latin America have joined the School. Presently, the School includes 52 Scientific Committee members from 17 different Countries. The PSA is one of the members of this school since its creation and Solar Treatment of Water Unit coordinates de European Branch. The Summer School is among the initiatives organized for School PhD candidates but other PhD students, MSc students, post-doctoral researchers and professionals. The 2019 edition (>120 attendants, UPV-Spain) was co-organised by Solar Treatment of Water Unit.

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

- Solar photocatalytic and photochemical processes as tertiary treatment for the removal of pollutants of emerging concern and microorganisms, related with, ECOSAFEFARMING (ERA-NET, WATER JPI), AQUACYCLE (CBC ENI MED) and PANIWATER (H2020-India) projects and AQUALITY Marie Skłodowska-Curie Action.
- Solar photochemical processes for the remediation of industrial wastewaters, related with UMA SOLAR (Network) and CALYPSOL project.
- Integration of Advanced Oxidation Processes with other water treatment technologies (NF/UF; Ozone, Bioprocesses, etc.), related with AQUALITY Marie Skłodowska-Curie Action and CALYPSOL project.
- Evaluating photocatalytic efficiency of new materials under solar light in pilot reactors, related with ECOSAFEFARMING (ERA-NET, WATER JPI), UMA SOLAR (Network), RATOCAT (ERA-NET) and CALYPSOL projects.
- Photocatalytic and photochemical processes for water disinfection in different scenarios related with WATERSPOUTT project and ALICE Marie Skłodowska-Curie Action.
- Pilot solar photo-reactors for production of hydrogen and other photo-fuels, related with RATOCAT (ERA-NET) project.

7.2 Projects

Network: Iberoamerican Solar Water Treatment Network (UMA SOLAR)

Participants: CIESOL- Universidad de Almería, CIEMAT y SERC Chile (Solar Energy Research Center, Código FONDAP 15110019)

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Funding agency: FONDECYT *Fondo Nacional de Desarrollo Científico y Tecnológico de Chile, Programa de Cooperación Internacional*.

Background: FONDAP, a program run by the National Commission for Science and Technology Research ini Chile, promotes the development of scientific research centers of excellence. These centers leave a strong impact, working within priority areas and "responding to extremely important and relevant problems for the country" and "forming and consolidating research teams." The development and widespread adoption of small-scale solar solutions in both, rural and urban communities will play an important role in the future as energy supply solutions of the country and a driver of productive applications. In this context, the SERC Chile RL1 (Solar Water Treatment), which is the research group coordinating this network, will develop its major effort in that focus. Therefore, consolidation/extension of a robust scientific community with a strong national/international cooperation network is a key factor.

Objectives: The network will foster collaboration among the research centers involved in UMA SOLAR, through the joint work of researchers, generating joint publications, presenting joint results in seminars and conferences, including PhD theses within the framework of the project and disseminating to the community the results achieved. Three main R+D collaborations are envisaged: solar treatment of water at pilot plant scale, new photocatalysits (materials) and solar mining.

Achievements in 2019: Activities carried out within UMA SOLAR Network were: Isabel Oller was invited to perform a lecture in the "*Curso Internacional de Transferencia de Conocimiento Tecnológico sobre la Energía Solar y Tratamiento Solar de Aguas de la Macro Región Centro Sur Andina (Chile, Perú y Bolivia)*". Two joing publications: "The influence of location on solar photo-Fenton: Process performance" in *Renewable Energy* Journal and "Modeling persulfate activation by iron and heat for the removal of contaminants of emerging concern using carbamazepine as model pollutant, photoreactor scaling-up and treatment cost" in *Chemical Engineering Journal*. Finally, Alejandro Cabrera Reina, PhD (Universidad de Tarapacá and Network responsible in Chile), and Lisdelys Gonzalez Rodriguez (Universidad Central de las Villas, Chile) made a Research stay at PSA from September to December 2019.

Water Sustainable Point of use Treatment Technologies, WATERSPOUTT

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

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

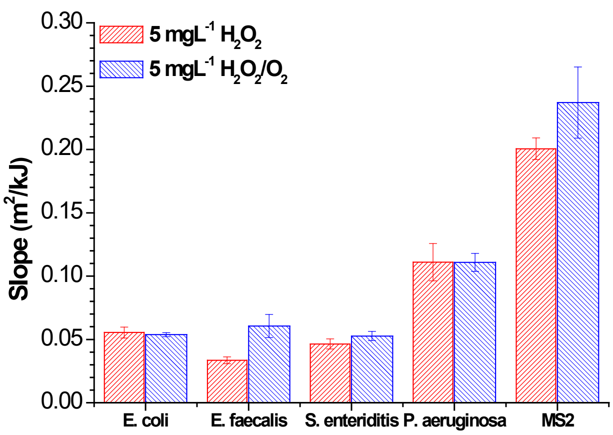
Background: Solar water disinfection (SODIS) is a household water treatment that uses direct sunlight to inactivate pathogens in water using 2-L PET bottles. It is widely accepted in developing countries, but some limitations still affecting the efficiency of this process such as the volume of water to be treated per batch (bottle).

Objectives: The main objective is to increase the user uptake of SODIS by designing and piloting three novel solar based technologies (Solar rainwater reactors, Solar jerrycans and Solar-ceramic filtration) providing larger volumes (≥20 L) of treated water per day. CIEMAT objective is to develop, construct and test reactors based on SODIS for disinfection of harvested rainwater providing 125 litres/day of treated water.

Achievements in 2019: During this year, CIEMAT has been investigating the effect of adding a chemical oxidant (H_2O_2) at very low concentration as well as the injection of air as key parameters to enhance the SODIS performance at pilot plant scale (Figure 96.a). An experimental design has been carried out to using 4 culture-type bacteria (*E. coli, Enterococcus faecalis, Salmonella enteritidis* and *Pseudomonas aeruginosa*) and a virus (MS2 bacteriophage) as model of waterborne pathogen commonly found in harvested rainwater. This investigation has set as its main goal the evaluation of the influence of adding very low concentrations of H_2O_2 (5 mg/L), increasing the dissolved oxygen and the combination of these two parameters on simulated rainwater solar disinfection process (Figure 96.b). The main findings have been the discarding of air sparging, even though a benefit on the inactivation was observed in some cases, due to its use implies an increment of the treatment cost. And according to the success results obtained with the addition of H_2O_2, a further toxicological analysis is pending to be carried out to ensure the drinking water quality.

On the other hand, the field studies related with the technologies developed on Waterspoutt project have continued been tested in Uganda (Solar reactors), South Africa (Solar reactors), Malawi (Solar buckets) and Ethiopia (Solar Jerry cans) in terms of water disinfection capability and social aspects. See also: website.

(a)



(b)

Figure 96. a) Solar CPC reactor prototype of 25 L under natural sunlight at PSA facilities. b) Inactivation kinetics constant of all pathogens tested with 5 mg/L-H_2O_2/Solar and 5 mg/L-H_2O_2/Solar/O_2

Accelerate Innovation in Urban Wastewater Management for Climate Change, ALICE

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

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

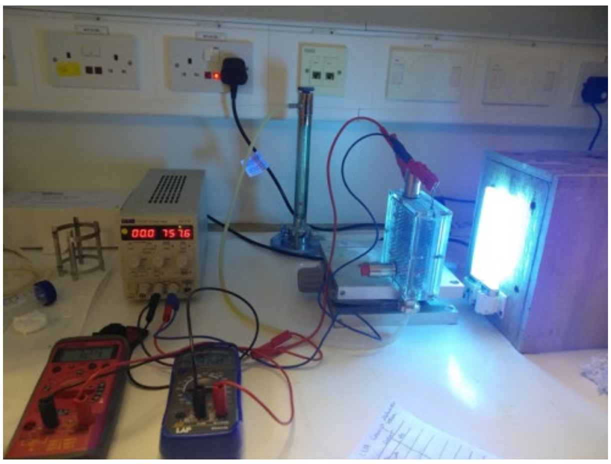
Funding agency: H2020- Marie Skłodowska-Curie Action (RISE) (GA 734560)

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

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

Achievements in 2019: In this year, an ER-secondment from CIEMAT in Northern Ireland Water Company and in the University of Ulster (in the Nanotechnology and Integrated Bioengineering Centre) took place in January 2019. During this collaborative stay, a complementary studied related with photo-electrocatalysis (PEC) to treat urban wastewater took place. The enhancement of PEC for water disinfection using holes' acceptors (methanol and acetate at concentration of 5 mM) were carried out using carbon felt as cathode and TiO_2-nanotubes as electrodes (Figure 97).

On the other hand, at CIEMAT, the efficiency of solar process to remove emerging contaminants and pathogens from wastewater and its further reuse for raw-eaten crops (lettuce and radish) have been continuously tested. See also: website.



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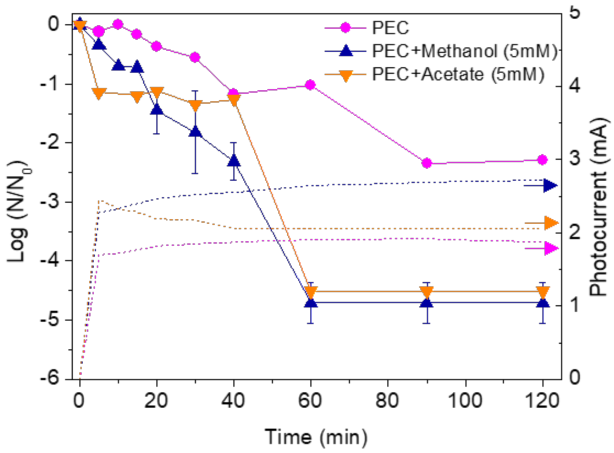


(b)

Figure 97. a) Laboratory scale set-up for photo-electrocatalysis (PEC) experiments at Ulster University facilities. b) Inactivation profile of *E. coli* by carbon felt-PEC treatment alone and in the presence of holes´acceptors.

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

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

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

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

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

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

Achievements in 2019: Mid-term review of AQUALITY project took place in the École Polytechnique Palaiseau in Paris (France) jointly with the workshop on Prioritization of Emerging Contaminants in Urban Wastewater and the International Winter School in Mass Spectrometry from the 4th to the 8th of March, 2019. During the Mid-Term review the Project Officer had a personal interview with each ESR giving finally a positive evaluation to the coordinator. Fourth coordination meeting of the project took place in KTU Osman, Trabzon (Turkey) the 2nd and 3rd of September 2019, followed by an International Conference on Chemical Energy and Semiconductor Photochemistry 4th and 5th of September 2019. Two ESRs (Early Stage Researchers) are doing their PhD in the Solar Treatment of Water Unit at PSA on the “Assessment of novel advanced oxidation processes for removal of disinfection-by-products and CECs from drinking water” and “Application of advanced integrated technologies (membrane and photo-oxidation processes) for the removal of CECs contained in urban wastewater”. Last results obtained by them related to the research WPs within AQUALITY project are shown in Figure 98 and Figure 99. For more details visit the website.

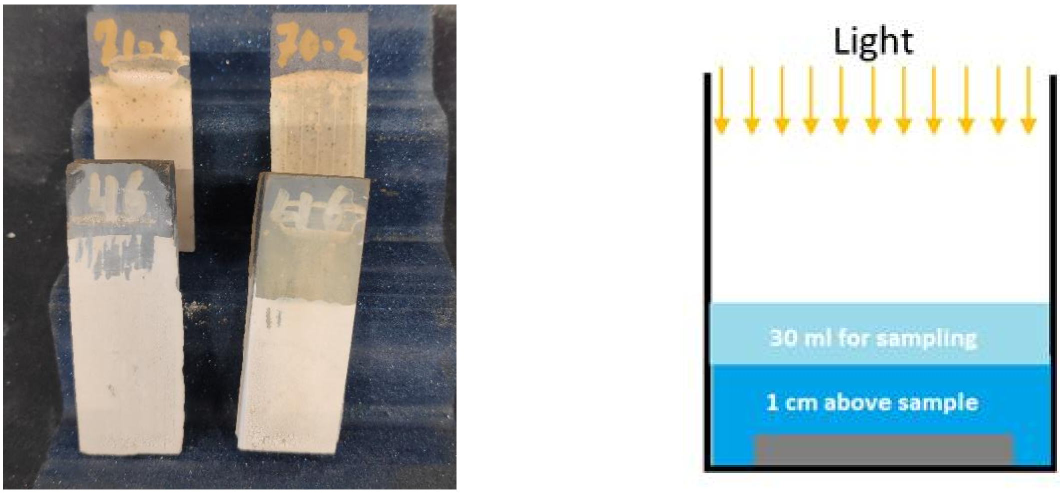
Development and testing of a novel photocatalytic system for efficient cogeneration of clean water and hydrogen for ecosafe agriculture, ECOSAFEFARMING

Participants: Istanbul University (Coord.), MIR Arastirma ve Gelistirme A.S. (Turkey), BUT - Brandenburg University of Technology (Germany), University of Ontario Institute of Technology (Canada), CIEMAT.

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

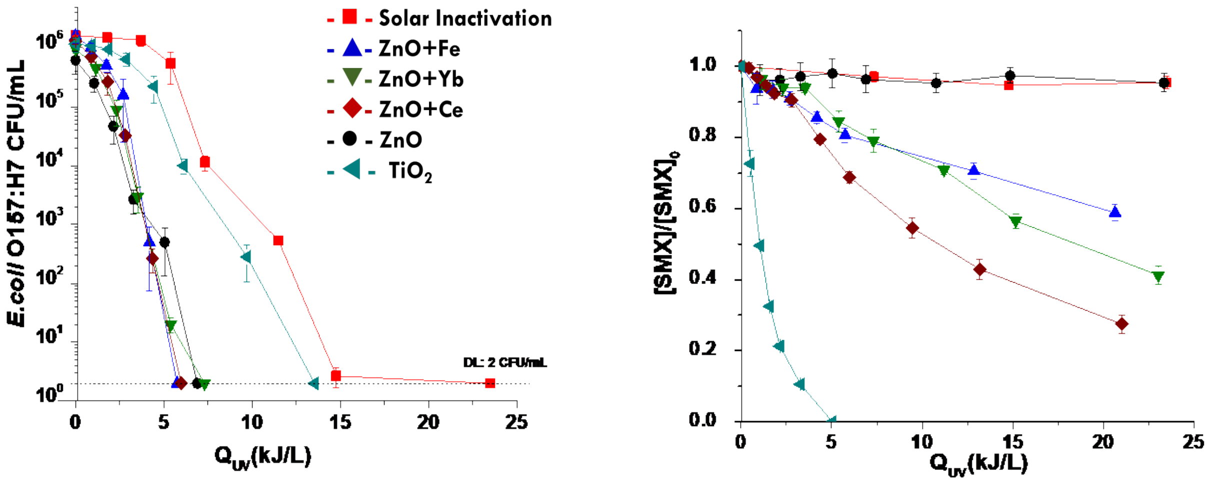
Funding agency: WATER JPI 2016, ERAN-NET COFUND WATEWORKS 2015 and Spanish Ministry of Economy and Competitiveness (Reference PCIN-2017-131).

Background: There has recently been increasing interest in urban wastewater (UWW) utilization for agricultural and hydrogen production as it agrees with the six main pillars of sustainable energy systems: (i) better efficiency; (ii) better cost effectiveness; (iii) better resources use; (iv) better design and analysis; (v) better energy security; and (vi) better environment.



(a) (b)

Figure 98. (a) New photocatalytic-UF membranes carried out in Liqutech within the AQUALITY project. (b) Schematic overview of the experimental set-up using a 250 ml beaker for testing new photocatalytic ceramic membranes (40x40) placed on the bottom.



(a) (b)

Figure 99. (a) Effect of new photocatalysts on the inactivation of E. Coli in simulated effluent of a municipal wastewater treatment plant. (b) Simultaneous elimination of Sulfametoxathole (SMX) in the same water matrix and with the same new developed photocatalysts (same legend as in (a)).

Objectives: The general aim of ECOSAFEFARMING is to develop and implement a novel and energy efficient tertiary treatment technology enabling reuse of UWW for safe agricultural irrigation. CIEMAT specific objectives are: Assessment of the performance of the lab-scale photocatalytic electrodialysis (PCED) reactor driven by sunlight for UWW purification, assessment of the optimized and scaled-up

PCED and H2-PCED reactors, experimental assessment of treated UWW for irrigation of raw eaten crops in an experimental greenhouse, quantitative Microbial Risk Assessment and techno-economic analysis of experimental data.

Achievements in 2019: Integration of PCED reactor for simultaneous production of clean water, H_2, electricity, and heat must be constructed by University of Istanbul. A synergistic study about the influence of location on solar photoreactors costs has been performed. A commercial iron fertilizer (Fe^{3+}-EDDHA) employed to remediate iron chlorosis in agriculture has been investigated for the first time as a promoting bactericidal agent in solar water disinfection processes. Irrigation tests with the treated wastewater were done (radish and lettuces crops) during 1.5 and 3 months, respectively.

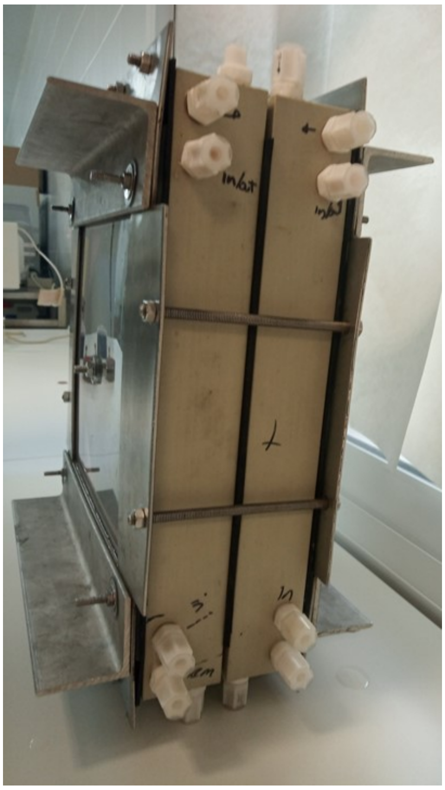


Figure 100. PCED reactor prototype constructed by University of Istanbul.

Rational design of highly effective photocatalysts with atomic-level control, RATOCAT

Participants: University College Cork (Tyndall National Institute-UCC, Ireland, Coordinator), Delft University of Technology (The Netherlands), Instituto de Ciencia de Materiales de Sevilla, CSIC (Spain), CIEMAT.

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

Funding agency: M-ERA.net H2020 through Spanish Ministerio de Economía y Competitividad (MINECO). Project PCIN-2017-131.

Background: RATOCAT project aims to develop improved photocatalyst materials along with the processes for their production through atomic-level control of structure and functionality. The target technology is the generation of hydrogen gas from water using solar energy, which is a crucial component of the global transition to renewable energy sources.

Objectives: (i) Absorption of the visible-light solar spectrum by tailoring surface-modified catalyst materials; (ii) Surface modification of catalyst powders with non-critical materials via a deposition process that is scalable to the manufacturing environment; (iii) Wastewater as the feedstock for hydrogen.

Achievements in 2019: According to 2018 results, a $CuO+TiO_2$ mixture, based on two commercial and well characterized CuO (CuO nanoparticles from Sigma Aldrich, average size of the CuO nanoparticles 50 nm) and TiO_2 photocatalyst (Degussa P25), has been used to produce hydrogen by solar light irradiation and in presence of different organic compounds. The tested system shown similar hydrogen generation capacity and energy efficiency than more expensive catalysts based on the use of noble metal/photocatalyst composites. A clear reduction of the Cu content has been detected by characterizing the sample obtained after 5 consecutive runs, a process that is in agreement with the deposition of the catalyst on the walls of the CPC reactor. Therefore, CuO did not leave the reactor but it remains on the CPC pyrex walls and continued doing its role. The UV-Vis-NIR diffuse reflectance spectra of the support P25, fresh catalyst and of the catalysts after 5 cycles are shown in Figure 101. After 5 cycles, the spectrum is similar to that of P25, showing a band gap of 3.17 eV, and indicating the absence of CuO.

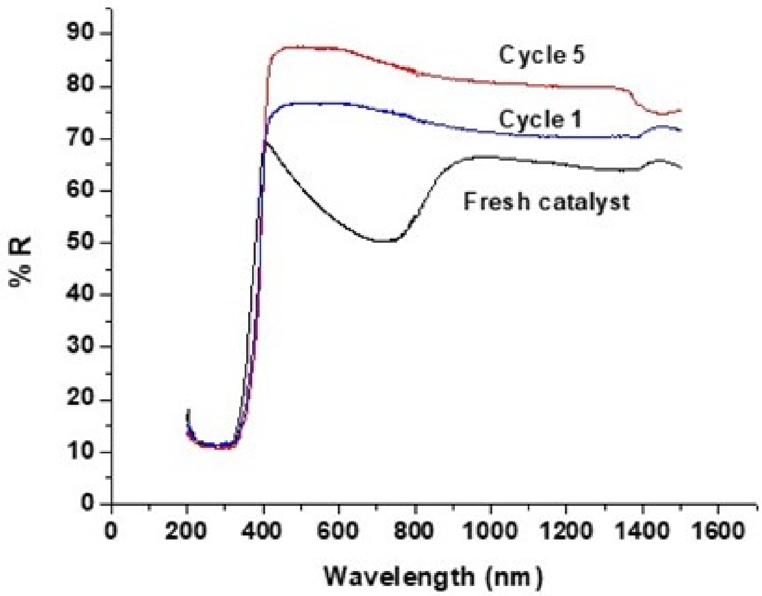


Figure 101. UV-Vis-NIR Diffuse reflectance spectra of the studied catalysts.

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

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

Salento, Buckinghamshire new University, Universidad de Santiago de Compostela, Society for Technology & Action for Rural Advancement.

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

Funding agency: H2020-SC5-2018-2019-2020/H2020-SC5-2018-1 (GA 820718)

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

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

Achievements in 2019: PANIWATER project began the 1st of February 2019 and the Kick off Meeting took place in New Delhi (India) along the 11th and 12th of February jointly with India-EU Water Forum World Sustainable Development the 13th of February and EU H2020 SC5-12-2018 Joint projects Event the 14th of February. During the Kick-off meeting each partner did a short five-minutes presentation with the objective of showing not only their general activities in the different institutions and companies, but also to specify their role in the WPs of the PANIWATER project. CIEMAT mainly participates as coordinator of WP2 of wastewater treatment and also in WP3 related to drinking water. Within the activities of WP2, several skype meetings have taken place within European partners and also jointly with Indian ones, to decide the physicochemical characteristics of the simulated wastewater to be tested as well as the CECs and pathogens and ARB&ARG which removal will be tackled. In the second semester of 2019 experimentation with UVC lamps pilot plant at PSA studying the effect of H_2O_2 and $S_2O_8^{2-}$ has been carried out for the simultaneous elimination of selected micro-contaminants (MCs) such as acetaminophen, caffeine, carbamazepine, trimethoprim, sulfamethoxazoleand diclofenac and pathogens such as *Escherichia coli*, *Enterococcus faecalis* and *Salmonella enteritidis*. The efficiency of UVC alone on microcontaminants elimination and pathogens inactivation is shown in Figure 102. For more details visit the website.

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

Participants: Univ. Politecnica de Valencia (UPV), Univ. Rey Juan Carlos, CIEMAT.

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

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

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

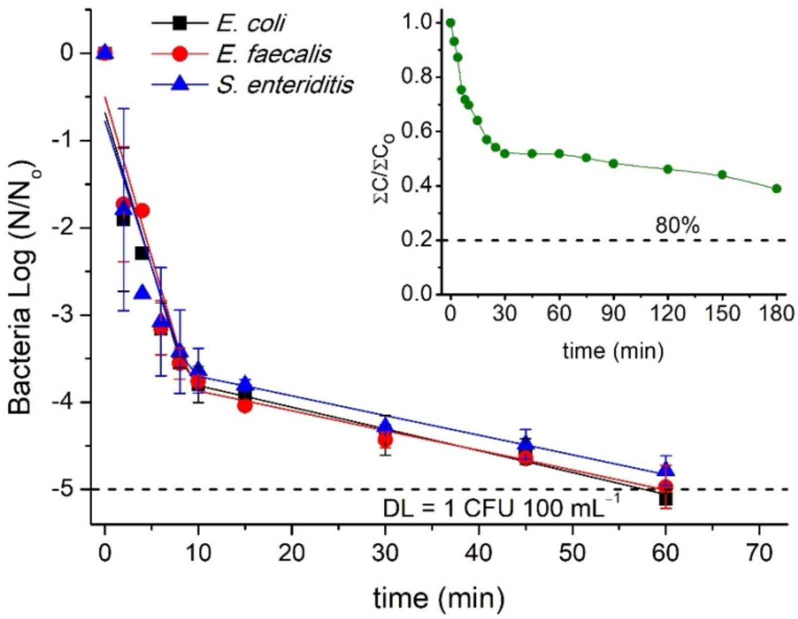


Figure 102. Simultaneous bacterial inactivation and MCs degradation (inset) under UVC radiation in simulated secondary effluent of a municipal wastewater treatment plant as a function of treatment time. Dashed lines refer to detection limit (DL = 1 CFU 100 mL-1) and 80% removal of total MCs.

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

Achievements in 2019: Different advanced were attained in WP2 (Technologies based on solar and novel oxidation processes for urban wastewater purification: simultaneous removal of cecs, antibiotic resistant bacteria (ARB) and AR genes (ARG)), WP3 (application of photocatalytic processes for industrial wastewater decontamination), WP4 (hybrid advanced technologies for wastes remediation, reusing and revalorization) and WP5 (assessment of BAT for abatement of CECs using solar energy to be used in southern EU compared with BAT available in northern EU). For example, experimental lab-procedures for analysis of target pollutants (Antibiotics, ARB and ARG) were developed, solar photo-Fenton process applied to imidacloprid degradation using different ZVI was performed and simultaneous bacterial inactivation and MCs degradation under UV-C radiation in municipal wastewater treatment plant (MWWTP) effluent was atained, between other tasks of the project.

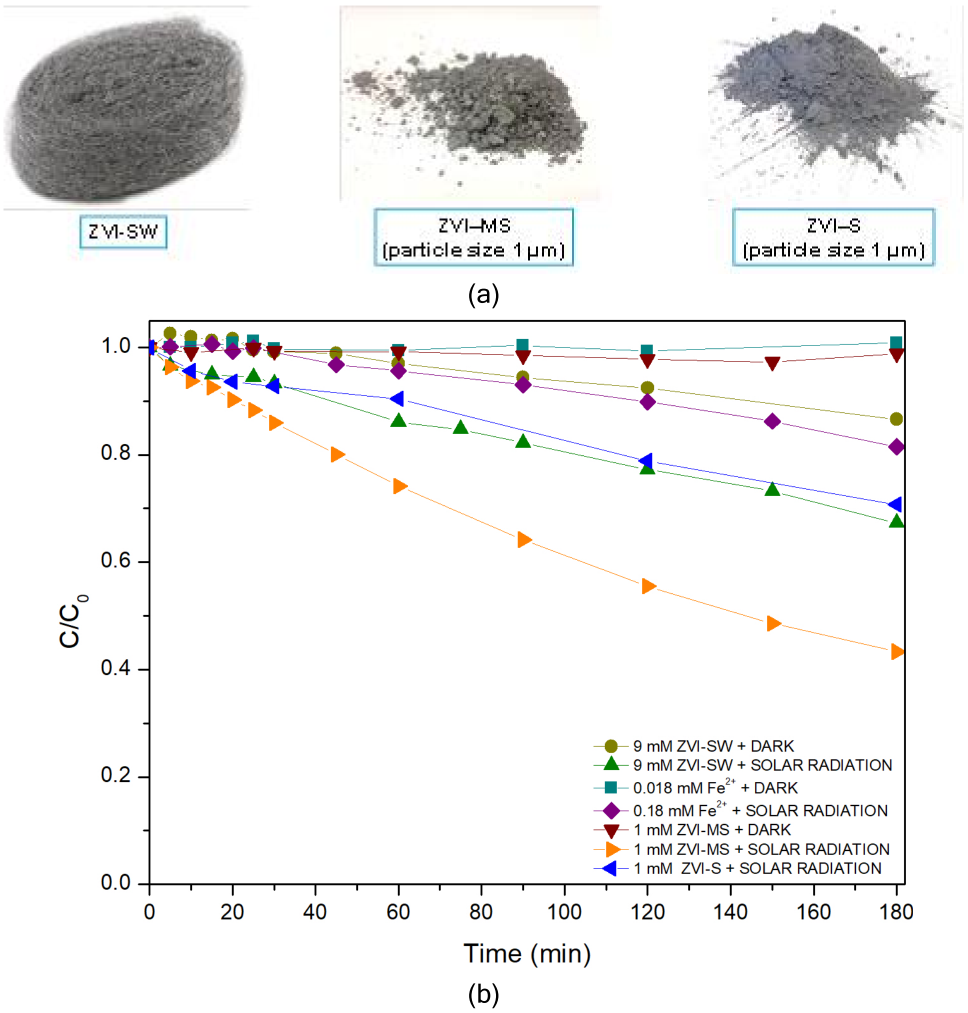


Figure 103. a) Different ZVI sources: (i) commercial steel wool (ZVI-SW), (ii) ZVI microspheres (ZVI-MS) and (iii) ZVI powder (ZVI-S). b): Imidacloprid degradation profiles by solar ZVI technology at neutral pH.

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

Participants: Centre of Research and Technology-Hellas (CERTH), CIEMAT, Integrated Resources Management (IRM), Holding Company for Water and Wastewater (Egypt), Centre for Water Research and Technologies (CERTE) and National Research Institute of Rural Engineering, Water and Forests (INGREF).

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

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

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

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

Achievements in 2019: AQUACYCLE project began the 1st of September 2019 and the Kick off Meeting took place in Thessaloniki (Greece) the 30th of September and 1st of October 2019. During the Kick off Meeting each partner present their institution as well as their role in the project. The members of the external advisory board attended telematically by skype. In addition, each work package leader performed a presentation of the main actions and activities to be carried out within the next six months of the project. CIEMAT leads work package 5 related to Operational demonstration and capacity building. Finally, great importance was given by the coordinators to financial and management issues. The A3 poster prepared for dissemination of AQUACYCLE activities is shown in

Figure 104. For more details visit the website.

Figure 104. AQUACYCLE dissemination poster.

8 Horizontal R&D and Innovation activities

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

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

Contacts: Ricardo Sánchez, ricardo.sanchez@psa.es

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

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

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

Achievements in 2019: In January 2019, CIEMAT successfully organized the SFERA-III project kick-off meeting, where the objectives and activities of the different tasks of the project were presented in more detail. In February, CIMEAT launched the call for proposals for access to the facilities offered by the different participants in the project. The campaign was a success with 64 proposals received, of which 19 proposals requested access to the CIEMAT installations. Of these 19 proposals, 12 were selected by the User Selection Panel and during the year 2019 access has been granted to 7 of them. During 2019, CIEMAT submitted the necessary documentation, prepared with the collaboration of all the interested partners, for the first phase of evaluation for the constitution of the EU-SOLARIS ERIC, which passed successfully, and started the preparation of the documents to be submitted during 2020 for the second and final phase of the evaluation.

The JRA1 Development of Test Procedures for Materials and Components of Thermal Storage Systems is coordinated by ATYCOS. In this WP there are 4 tasks in 3 of which ATYCOS is actively involved. During 2019 a general methodology for validating materials as storage media has been proposed (Task 6.2). Discussion on the test procedures for prototype testing have been performed and the definition of KPIs from experimental results have been distributed between different partners (Task6.3). In collaboration with the Thermal Storage Working Group of SolarPACES task III, which is also coordinated by ATYCOS experts, the critical components in molten salt loops have been identified (Task 6.4).

Figure 105. Photo of the participants in the kick-off meeting held at the PSA.

8.2 Integrating National Research Agendas on Solar Heat for Industrial Processes, INSHIP

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

Contacts: Julian Blanco, julian.blanco@psa.es
Diego Martínez, diego.martinez@psa.es

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

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

Agenda-ECRIA) designed by the European Commission as the next step beyond the current Integrated Research Agendas (IRP) and specifically targeting EERA JPs.

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

Achievements in 2019: In addition, to coordinate WP6 (Integrated SHIP research infrastructures) and WP8 (Advanced Networking Activities), PSA also participated into the research activities contributing to WP2 (Technology and applications to low temperature, 80-150°C) in the design of auxiliaries and BoP for low-temperature thermal desalination technology and assessing suitable alternatives for large-aperture solar static fields to reduce and stop solar collection (automatic cover system). In WP3 (Technology and applications to medium temperature, 150-400°C) providing two deliverables: “Guidelines for solar steam integration in steam networks: systems layouts, solar field control strategies, BoP components, safety procedures” and “Demonstration of cost-effective solar steam integration layout (experimental procedures)”. In WP4 (Technology and applications to high temperatures, 400-1500°C) PSA collaborated in the solar lime production for the cement industry by studying the thermal performance of a solar receiver at different operational conditions and defining suitable ways of obtaining regulation of transients to avoid continuous start-up and shutdown operations. In addition, PSA contributed to new solar chemical reactor concepts for the gasification of carbonaceous materials by assessing the advantages and limitations of different reactor configurations, focusing on batch vs. continuous process operation. Also, in this WP and in 2019, PSA developed the concept of a new concentrator system providing a vertical beam for solar chemical reactors without the need of active cooling.

Figure 106. INSHIP Management Board Meeting (Freiburg, Germany, 8th May 2019).

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

Participants: ESTELA (Belgium), CIEMAT (Spain), ENEA (Italy), DLR (Germany), METU (Turkey).

Contacts: Julian Blanco, julian.blanco@psa.es
Eduardo Zarza, eduardo.zarza@psa.es

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

Background: Coordination and support action to provide support to the realisation of the Implementation Plans of the SET-Plan and, specifically in this case, to the CSP one. Following the selection of relevant European countries for efficient deployment of CSP/STE, the project proposes solutions and pathways for overcoming the essential shortcomings of the current national strategies related to CSP/STE that are: a) for the industry: the legal framework conditions for the procurement of manageable RES; and b) for the R&I sector: entering in working relations with national funding agencies with the objective of extending to more public funding agencies and other sources the funding of R&I projects already ranked by all European CSP/STE stakeholders according to their expected impact on the sector. These projects were integrated into the Implementation Plan (IP) of SET-Plan.

Objectives: 1) Assessment of the conditions required for replicating in European countries the commercial cost levels (< 10€ cents/kWh) that already achieved by the industry on CSP/STE world markets (financial conditions, type of auctions, the contribution of innovations delivered by R&I) and paving the way for the implementation of FOAK projects as one of the objectives of the Initiative and its Implementation Plan. 2) Assessment of the conditions required for replicating in European countries the commercial cost levels (< 10 ct./kWh) that already achieved by the industry on CSP/STE world markets (financial conditions, type of auctions, the contribution of innovations delivered by R&I) and paving the way for the implementation of FOAK projects as one of the objectives of the Initiative and its Implementation Plan. 3) Active promotion of the introduction of CSP/STE into energy strategy policies at European or national levels.

Achievements in 2019: In the field of research activities, the first submitted deliverable addressed a proposal for the funding agencies to prioritize IP projects and actions. Regarding this issue, a broad survey was made to gather the interest of the stakeholders regarding the participation in R&I and First-of-a-kind projects. This survey was based on the 12 R&I Actions defined in the SET-Plan from September 2017, from which the 8 topics selected by the consortium CSP-ERANET were used in the Survey: This report has the overall objective to analyse the outcome of a CSP/CST stakeholder survey and to give recommendations to the funding agencies for the next Call for Proposals in the CSP ERA-Net program. Among the found results, it was found that the potential number of qualified stakeholders for high TRL activities does not match the available national budget in some cases. Stakeholders from 15 countries participated, being Spain, Turkey, Germany, and Italy the highest (by this order) from the number of participant's point of view. Also, it was submitted a second deliverable proposing specific indicators and methodology for monitoring the success of the execution of the IP. Two types of Technical Indicators and Target Objectives were defined for all activities: quantitative indicators, addressing measurable properties or characteristic such as temperature, capacity (electrical or thermal), unit cost, etc., and qualitative indicators, e.g. technical level, scalability etc.

Figure 107. HORIZON-STE Kick-off Meeting (Brussels, Belgium, 7th May 2019).

9 Training and educational activities

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

The main features of this training program are:

- Management of the Ph.D. fellowship program in association with the University of Almeria (UAL) and CIEMAT's own program for young researchers.
- Management of miscellaneous educational cooperation agreements with other entities that bring students to the PSA (Universities of Almería, Dalarna-Sweden, Antofagasta-Chile, Federal de minas Gerais-Brasil,Ponticicia Católica-Chile, Autónoma de Zacatecas-México, Osnabrück, Federal Sao Carlos-Brasil, Juarez Autónoma de Tabasco-México, Salerno-Italy)

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

Related with the Educational Cooperation Agreement between CIEMAT and the University of DALARNA (Sweden), the "Solar Thermal Power" course was given by PSA researchers in the framework of the Master Programme in Solar Energy Engineering. With 5 credits, this course takes part during the 2nd cycle of this Master Programme organized by the European Solar Engineering School, ESES (University of Dalarna). The first part of the CSP training course was hold from 2nd to 6th September and consisted on the theory lessons, tought by two researchers from CIEMAT at Dalarna University (Börlange, Sweden), while during the second part of the CSP training course, the students came to CIEMAT to visit the facilities from 14th to 16th October.

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

The First SFERA summer school was held from September 9th to September 11th, 2019 at the premises of the CNRS-PROMES laboratory and it was focused on Thermal energy storage systems, solar fields, and new cycles for future CSP plants. Afterward, the Doctoral Colloquium was hosted at the same location from September 11th to September 12th only for SFERA Members.

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

10 Events

23-24/01/2019

Official Kick-off Meeting

The SFERA-III project kick-off meeting was held at the PSA in Almería (Spain).

05-06/03/2019

Official Workshop

Guillermo Zaragoza was invited to participate and present in an expert group gathered by the JRC of the European Commission to discuss all aspects of sustainable desalination for its implementation.

21/03/2019

Official meeting

Meeting of the Water Europe Working Group on Renewable Energy Desalination organized by Guillermo Zaragoza in Brussels.

22/03/2019

Technical visit

A group of 20 students from the University Politecnica of Valencia visited PSA facilities as part of the activities program of the course.

25/03/2019

Lecture

Invited lecture by Guillermo Zaragoza on the course “Dessalement par les energies renouvelables et la purification des eaux” organized by Centre de Recherche en Technologie des Semi-conducteurs pour l'Energétique in Algiers (Algeria).

26/03/2019

Lecture

Isabel Oller was invited to give a lecture in the “Two-day intensive course on solar driven desalination and water purification” held at the CRTSE (Centre de Recherche en Technologie des Semi-conducteurs pour l´Energéttique) in Alger (Algeria).

03/04/2019

Technical visit

A group of students and two teachers of the Renewable Energies Master of Exeter University (United Kingdom) visited the PSA interested to receive information about all the research facilities.

10/04/2019

Technical Visit and Official Meeting

The Task 55 Solar Heating and Cooling Programme (SHC) International Energy Agency (IEA): Towards the Integration of Large SHC Systems into DHC Networks, celebrated its 6th Expert Meeting from the 8th to the 10th of April 2019 in Almería. The expert meeting was followed by a technical visit to the PSA tests facilities.

12/04/2019

Institutional visit

Visit of the Economic Affairs and Infrastructures Councillor of the Region of Extremadura and the President of ENRESA to explore possible ideas to increase and optimize industrial development in Extremadura region in association with new future CSP/STE commercial power plants to be constructed in the region.

29-30/04/2019

Lecture

Sixto Malato, Isabel Oller and Manuel I. Maldonado were invited to give lectures in the "*Curso-Taller de actualización en Procesos Avanzados de Oxidación: Nuevos desarrollos ambientales de los Procesos Avanzados de Oxidación*" held at the Universidad de Caldas in Manizales (Colombia).

The course was organised within the activities dedicated to honour the retirement of Prof. César Pulgarin at the Swiss Federal Institute of Technology (EPFL, Switzerland), a key figure in the area of Catalytic Advanced Oxidation Processes and born in Manizales.

07-08/05/2019

Lecture

Keynotes from Dra. Loreto Valenzuela and Dr. Diego Alarcón in the Seminar: "*Desalinización y Tratamiento Solar de Agua: Tecnologías y Aplicaciones*" held at the Pontificia Universidad Católica de Chile. Santiago de Chile, Chile.

08/05/2019

Invited Lecture

Sixto Malato was invited to give a lecture "Solar AOPs for wastewater treatment: overview of processes and photoreactors" in the II Sustainable Raw Materials International Project Week and Scientific Conference organised at the University of Szeged in Szeged (Hungary) during 6-10 May 2019.

15/05/2019

Lecture

Isabel Oller was invited to give a lecture in the session titled "Solar Energy & Water - The Nexus of Two Essential Ingredients for Life" at the INTERSOLAR Europe in Munich (Germany).

22/05/2019

Talk in Pint of Science Festival

Description: Isabel Oller participated as a speaker in the event of Pint of Science that was celebrated in Almería (Spain) under the name “ZH2ON-2” and with the title “*El papel del agua en el cambio climático*”.

23/05/2019

Invited lecture

Sixto Malato was invited to give a lecture at the “*III Feria Internacional de Agricultura Intensiva Infoagro* Exhibition 2019” celebrated in Roquetas de Mar (Almería) and with the title “*Tratamiento de efluentes de EDAR mediante procesos avanzados de oxidación basados en radiación solar: ¿un nuevo recurso hídrico para regiones áridas?*”.

03-06/06/2019

Lecture

Isabel Oller, Inmaculada Polo and Sixto Malato were invited to give lectures at the 3rd European Summer School of Environmental Applications on Advanced Oxidation Processes organized at the UPV-Campus of Alcoy (Spain). Isabel Oller also participated on the round table “The researcher´s career”. Sixto Malato co-organized the event as Regional Coordinator for Europe of the "International PhD School on AOPs".

12/06/2019

Official meeting

Meeting of the Water Europe Working Group on Renewable Energy Desalination organized by Guillermo Zaragoza in Brussels.

13-14/06/2019

Invited Lecture

Sixto Malato was invited to give a lecture at the “I SIMPOSIA NOVEDAR” (*presencia y eliminación de microcontaminantes en agua*) organised by Universidad de Santiago de Compostela and with the title “*Eliminación de microcontaminantes mediante procesos de oxidación avanzada: tecnologías de tratamiento y evaluación de resultados*”. This symposium was held at the Monasterio San Martín Pinario in Santiago de Comnpostela (Spain).

18/06/2019

Doctoral Thesis

Margarita Rodríguez García, from the Thermal Storage and Solar Fuels Unit, defended the Doctoral Thesis “*Contribución al diseño y ensayo de sistemas de almacenamiento energético mediante sales fundidas para plantas termosolares*”. University of Almeria, Almería (Spain).

23/06/2019

Lecture

Invited lecture by Guillermo Zaragoza on the Workshop on Membrane Distillation organized during the International Water Association (IWA) Membrane Technology Conference & Exhibition for Water and Wastewater Treatment and Reuse (IWA-MTC 2019) Conference in Toulouse (France).

25/06/2019

Study visit

Study Visit of EU-CELAC Working Group on Research Infrastructures to the PSA to analyse opportunities to strengthen the bi-regional collaboration in CSP technologies.

05/09/2019

Institutional visit

Visit of the Mayor of Lucainena and a Swiss delegation from Brienz in order to promote culture, communication and possible internships at our facilities.

10/07/2019

Lecture

Invited lecture by Guillermo Zaragoza on the EU-China Conference on Innovation and Membrane Technology in Weihai (China).

17/07/2019

Invited Lecture

Isabel Oller was invited to give a lecture during the "*Curso Internacional de Transferencia de Conocimiento Tecnológico sobre la Energía Solar y Tratamiento Solar de Aguas de la Macro Región Centro Sur Andina (Chile, Perú y Bolivia*)" at the SERC-CHILE-Universidad de Tarapacá in Arica (Chile).

20-22/09/2019

Invited Lecture

Sixto Malato was invited to give a lecture in "Polish Scientific Networks: Science & Technology" organised by Polish Foundation of Science and Polish Ministry of Higher Education at the Technical University of Poznan in Poland. He also participated in the round table "Innovation: what does it means?" with Prof. Leon Gradoń and Prof. Robert J. Cava (Princeton University, USA).

26/09/2019

Doctoral Thesis

Ana Ruiz defended the Doctoral Thesis "Integration of solar photochemical processes with other advanced techniques of analysis for the treatment and revalorization of complex wastewater". University of Almeria, Almeria (Spain).

09-10/10/2019

Official Meeting

Participation of Rocío Bayón at the 6th Experts Meeting of the Task 58/Annex 33 on Compact Thermal Energy Storage, organized by the Università degli Studi di Messina at the Fondazione Horcynus Orca in Messina (Italy).

14/10/2019

Lecture

Keynote presentation by Guillermo Zaragoza on the SUST-WATER 2019 conference organized by the Solar Equipment Development Unit UDES of the Renewable Energy Development Center (CDER) in Tipaza (Algeria).

15/10/2019

Technical Visit and Official Meeting

A steering committee meeting of the EU project PANIWATER with the international partners involved was held at PSA. During this event, technical discussions and a visit to the PSA facilities took place.

30/10/2019

Lecture

Isabel Oller was invited to give a talk to High School students about her experience as a researcher and why she decided to study a STEM career. The event took place at the Parque Tecnológico de Almería (PITA) in the frame of the project "*Ciencia y Tecnología en femenino*" (with the collaboration of APTE and FECYT).

31/10/2019

Official meeting

Meeting of the Water Europe Working Group on Renewable Energy Desalination organized by Guillermo Zaragoza in Brussels.

12-15/11/2019

Invited Professor

Sixto Malato was invited as professor to the 15-hour course "*Tópicos avançados em Processos Avançados de Oxidação mediados pela radiação solar*", taught in English to the master and doctorate students of the chemistry department, at the Federal University Rio Grande do Sul in Porto Alegre (Brazil).

18-22/11/2019

Plenary Lecture

Sixto Malato was invited to give a plenary lecture “Solar Photo-Fenton: Applications at Conventional and Neutral pH” at the IV Iberoamerican Conference on Advanced Oxidation Technologies (IV CIPOA) in Natal (Brazil).

02/12/2019

Awards

Maria Castro, Alba Ruiz, and Laura Ponce received a distinction from the University of Almeria (Spain) recognizing their Doctoral Thesis.

02/12/2019

Lecture

Sixto Malato was invited to give a talk to professionals and scientists at the “*II Jornada Científico-Técnica CÁTEDRA DAM, El agua residual como fuente de recursos*” organised by Catedra DAM of the Universidad de Valencia, and held at the Fundació Universitat Empresa-ADEIT, Valencia (Spain).

03/12/2019

Dissemination event at COP25

Description: Researches belonging to Group of Solar Treatment of Water from CIEMAT attended the “Cumbre del Clima (COP25)” held in Madrid (Spain). The delegated showed the main research activities of the group to a wide range of public (from scholars to scientific) attending this event.

13/12/2019

Conference

The PSA hosted the Final Conference of the EU H2020 WASCOP project, organized by Aránzazu Fernández-García, where several tools to reduce the water consumption in CSP plants (both in the cooling of the power block and in the cleaning of the optical surfaces) were presented by 16 speakers to 30 attendees.

18/12/2019

Doctoral Thesis

José A. Carballo, from the Solar Desalination Unit, defended the Doctoral Thesis “Modeling and Optimization for Efficient Resource Management in Thermosolar Technology”. University of Almeria.

19/12/2019

Technical visit

A group of 40 students and professors from the University of Murcia visited the PSA facilities as part of the activities program of their project 17 ODsesiones.

11 Publications

PhD Thesis

Rodríguez García, Margarita Manuela (2019). Contribución al diseño y ensayo de sistemas de almacenamiento energético mediante sales fundidas para plantas termosolares. Universidad de Almería, Almería.

Ruiz Delgado, Ana (2019). Integration of solar photochemical processes with analytical advanced techniques for the treatment and revaluation of complex wastewater. Universidad de Almería, Almería.

Soriano Molina, Paula (2019). Kinetic modeling of solar photo-Fenton process for micropollutant removal from municipal WWTP effluents in low-cost reactors. Universidad de Almería, Almería.

Solar Concentrating Systems Unit

SCI PUBLICATIONS

Aguilar, R., Valenzuela, L., Ávila-Marín, A.L., García-Ybarra, P.L., Simplified heat transfer model for parabolic trough solar collectors using supercritical CO2. *Energy Conversion and Management* 196 (2019), 807-820. DOI: https://doi.org/10.1016/j.enconman.2019.06.029

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PRESENTATIONS AT CONGRESSES

Oral presentations

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Wette, J., Sutter, F., Buendía-Martínez, F., Fernández-García, A. Effect of long term outdoor exposure on anti-soiling coatings for solar reflectors. *25th SolarPACES Conference*, October 1-4, 2019. Daegu, South Korea.

Posters

Buendía-Martínez, F., Fernández-García, A., Sutter, F., Wette, J., Martínez-Arcos, L., Reche-Navarro, T.J. Effect of the solarization in concentrating solar thermal components under accelerating aging tests. *25th SolarPACES Conference*, October 1-4, 2019. Daegu, South Korea.

Christodoulaki, R.I., Valenzuela, L., Biencinto, M., González, L. INSHIP Dimensioning tool for the balance of plant of solar heat for industrial processes system. *25th SolarPACES Conference*, October 1-4, 2019. Daegu, South Korea.

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Thermal Storage and Solar Fuels Unit

SCI PUBLICATIONS

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PRESENTATIONS AT CONGRESSES

Oral presentations

Lessons Learnt During the Construction and Start-Up of 3 Cylindrical Cavity-Receivers Facility Integrated in a 750 kW Solar Tower Plant for Hydrogen Production. Aurelio Gonzalez, Thorsten Denk y Alfonso Vidal 25th SolarPACES Conference, 1-4 October. Daegu, South Korea 2019. Oral presentation.

Solar Desalination Unit

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Energy Efficiency in Building R&D Unit

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PRESENTATIONS AT CONGRESS

Guest lectures

M.J. Jiménez. "Round Robin Test Box. Experiment set up and data". Presented at DYNASTEE Summer School 2019 on Dynamic Calculation Methods for Building Energy Assessment. Organised by the University of Granada, CIEMAT (Spain) and DYNASTEE-INIVE. 9-20 September 2019. Granada.

M.J. Jiménez. "PRACTICAL ASPECTS OF MODELLING IN DIFFERENT CASE STUDIES: Integrated PV ventilated systems". Presented at DYNASTEE Summer School 2019 on Dynamic Calculation Methods for Building Energy Assessment. Organised by the University of Granada, CIEMAT (Spain) and DYNASTEE-INIVE. 9-20 September 2019. Granada.

M.J. Jiménez. "Guidelines to dynamic analysis. Different approaches and physical aspects". Presented at DYNASTEE Summer School 2019 on Dynamic Calculation Methods for Building Energy Assessment. Organised by the University of Granada, CIEMAT (Spain) and DYNASTEE-INIVE. 9-20 September 2019. Granada.

Oral presentations

M.J. Jimenez. (In Spanish). “Grupo 2. Módulos, celdas y recintos de ensayo”. Presentado en “I JORNADA RED MONITOR. PROYECTO BIA2017-90912- REDT.” 30 mayo 2019, at the “Instituto de Ciencias de la Construcción E. Torroja-(CSIC)”. Madrid.