Plataforma Solar de Almería

Annual Report 2004

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Introduction

Plataforma Solar de Almería (PSA) activities in 2004 were structured around three main lines of work: solar thermal power production technologies, use of solar radiation for environmental applications, and activities directed at spreading and diffusing knowledge of the possible applications of these technologies on as wide a scale as possible.

At the time of writing, PSA research activity is structured differently from 2004. It is now organized into three Units, two of them research and one called **'PSA Management'**, devoted to horizontal management of resources, training and technical support for the other two units. The two research units are called **'Solar Concentrating Systems' (SCS)** and **'Environmental Applications of Solar Energy and Characterization of Solar Radiation' (AMES)**. The new SCS unit combines the activities of the old 'Mid-Temperature Solar Thermal Energy' and 'High-Temperature Solar Thermal Energy' projects. It also assumes the activities performed in the 'very high concentrating' facilities, the Solar Furnace and DISTAL, which formerly were part of the 'Training and Access Project'.

However, given that our activities in 2004 were carried out according to the old organization, the structure of this report is based on the old organization model.

In the 'Mid-Temperature Solar Thermal Energy' project, work on consolidation of the Direct Steam Generation technology, with which it is expected to reduce solar thermal electricity production costs by about 30%, continues to be ongoing. The heart of this activity has been the European INDITEP project, the purpose of which is to produce the detailed engineering of a 5-MW_e DSG plant. The experience accumulated during the years of continued operation of the PSA DISS plant will be a decisive factor in the success of this project.

During 2004, activities directed at clearing up the last technological unknown in the DSG process, thermal storage, were also begun. The 45-month DISTOR project, which receives support from the European Commission, officially began in February 2004. Its main purpose is the development of a competitive thermal storage system suitable for solar plants with direct steam generation in the solar field. To this end, a storage system based on phase-change materials has been developed.

The economic target of the DISTOR project is to achieve a specific storage system cost of 20€ per kWh capacity, since this figure would make their implementation in commercial solar thermal plants profitable. The DISTOR project, which has 13 participants from five countries, is coordinated by DLR.

The activity carried out in the 'High-Temperature Solar Thermal Energy' project focused on technological collaboration with the companies promoting the two commercial tower projects. The first, called PS10, which will be the first commercial solar thermal power plant in Spain, is due to be inaugurated in June 2006. The second initiative, called SOLAR THREE, which is still in the project stage, is based on the use of molten salts as the working fluid in a central receiver system.

'Solar fuels' also have their niche in the activities of this group, with special importance assigned to hydrogen production. Phase 1 of the project, undertaken along with Petroleos de Venezuela, S.A. and the ETH of Zürich was satisfactorily completed this year. This phase consisted of a kinetics study of the high-temperature chemical process required to transform heavy oil into hydrogen and demonstration of its feasibility using concentrated solar energy.

General PSA activities received an important boost from the new legal framework defined by Royal Decrees 436/2004 (BOE of 27/03/2004) and 2351/2004 (BOE of 24/12/2004). This new legislation has catalyzed Spanish industrial activity in this area. The 0.18€/kWh premium set for electricity generated by solar thermal energy, along with the possibility of hybridizing with 12% to 15% natural gas annually, has strengthened interest in solar concentrating technologies in the investment and industrial sectors. These attractive conditions have caused a large number of companies to come to the PSA seeking consultation and collaboration.

Our 'Environmental Applications of Solar Energy' activity has concentrated on detoxification of waste water and desalination of sea water. An important milestone was the startup of the first commercial solar detoxification plant in the world for treatment of rinse water from recycling of pesticide containers. This project is promoted by the 'Albaida Recursos Naturales y Medioambiente' company and is based on scientific and technological developments at the Plataforma Solar de Almería during recent years.

In 2004, the 'Associated European Solar Energy Laboratory' (SolLAB) was formally established. This virtual laboratory is made up by the main European institutes in concentrated solar energy research: IMP-CNRS of Odeillo (France), the DLR Solar Energy Division (Germany), the Federal Institute of Technology Renewable Energies Laboratory in Zurich (Switzerland) and CIEMAT itself. The agreement was signed in October 2004 and the coordinated tasks have already begun to produce fruit, especially in the flux and temperature measurement campaigns and training of Ph.D. students, and the 'Paul Scherrer Institut' of Switzerland has formally applied for membership.

On the other hand, continuous and intense collaboration with the University of Almería (UAL) has been consolidated with the creation of a mixed CIEMAT-UAL center or joint research in solar energy applications. This collaboration will be physically located in a new laboratory building partially financed by the ERDF program to be inaugurated at the UAL in 2005.

Training and dissemination activities continue strong, as we are well aware that we must not ignore our facet of informing society about the existence of this option among the renewable energies. Educational agreements are maintained with several different universities and research centers around the world.

The new 'Visitors Center', which we have been equipping with solar technology demonstration units all year long thanks to a subsidy from the Ministry of Education and Science, will play an important role in this area.

I would not like to end this introduction without expressing my appreciation for the support received from the CIEMAT Directorate General and the fine work and professionalism of all the PSA staff this year.

Diego Martínez Plaza
Director of the Plataforma Solar de Almería

General Presentation

The PSA as a Large Solar Facility: General Information

The Plataforma Solar de Almería (PSA), a dependency of the Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (CIEMAT), is the largest center for research, development and testing of concentrating solar technologies in Europe. PSA activities form an integral part of the CIEMAT Department of Energy as an R&D division.

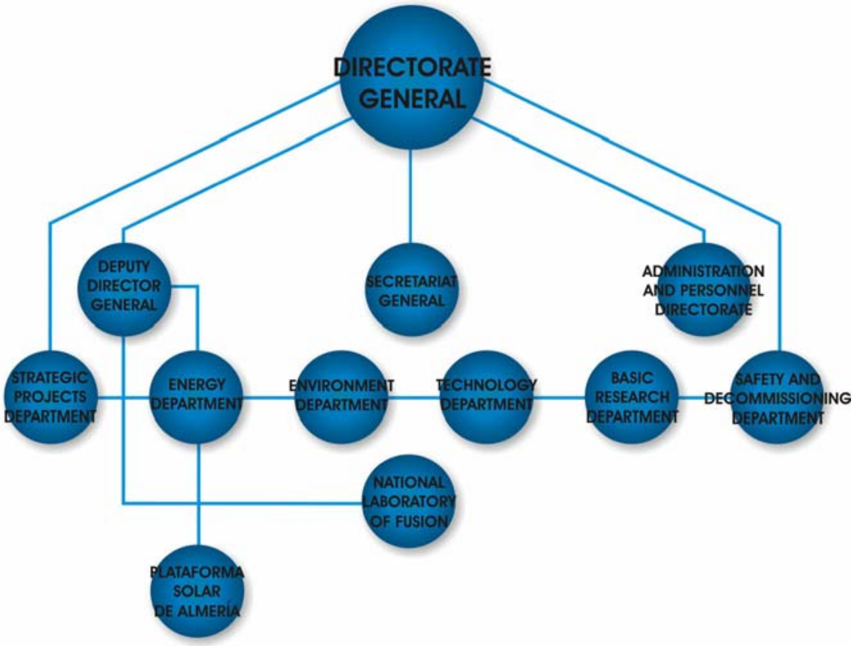


Figure 1. Integration of the PSA in the CIEMAT organizational structure

The objectives that inspire its research activity are the following:

- Contribute to a sustainable, clean, world energy supply.
- Contribute to conservation of European energy resources, climate and environment.
- Promote market introduction of solar thermal technologies and derived solar chemical processes.
- Contribute to the development of a competitive Spanish solar thermal export industry

Figure 2. Aerial view of the Plataforma Solar de Almería

- Reinforce the cooperation between business and scientific institutions in the field of solar thermal technology research, development, demonstration and marketing.
- Foster costs-reducing technological innovations leading to increased market acceptance of the solar thermal technologies.
- Assist industry in identifying market opportunities related to solar thermal technologies.

Organization and Functional Structure

In 2004, activities at the Plataforma Solar de Almería were structured around three large research projects or programs: 'Mid-temperature Solar Thermal Energy', 'High-temperature Solar Thermal Energy', and Environmental Applications of Solar Energy and Characterization of Solar Radiation'. The two first are devoted to the development of new and better ways of solar thermal power generation, and the third to exploring the chemical possibilities of solar energy, especially insofar as its potential for detoxification of industrial effluents, synthesis of fine chemicals and water desalination.

Supporting the above-mentioned research projects, the PSA has the corresponding areas of management and services, which, given the variety and complexity of the facilities, are of the greatest importance to the daily management of all the lines of activity that take place here.

Each R&D project is run by a project head and a technical staff on whose work the master lines of scientific activity and technological development at the PSA rely. They are largely independent in the execution of their budgets, the planning of their scientific objectives and the technical management of their resources. However, the three R&D projects share many PSA resources, services and infrastructures, so they must all be fluently communicated with the technical and administrative support units through the Director's Office, which has to see that the support capabilities, infrastructures and human resources are efficiently distributed. It is also the Director's Office which channels the demands to the various general CIEMAT support units located in Madrid.

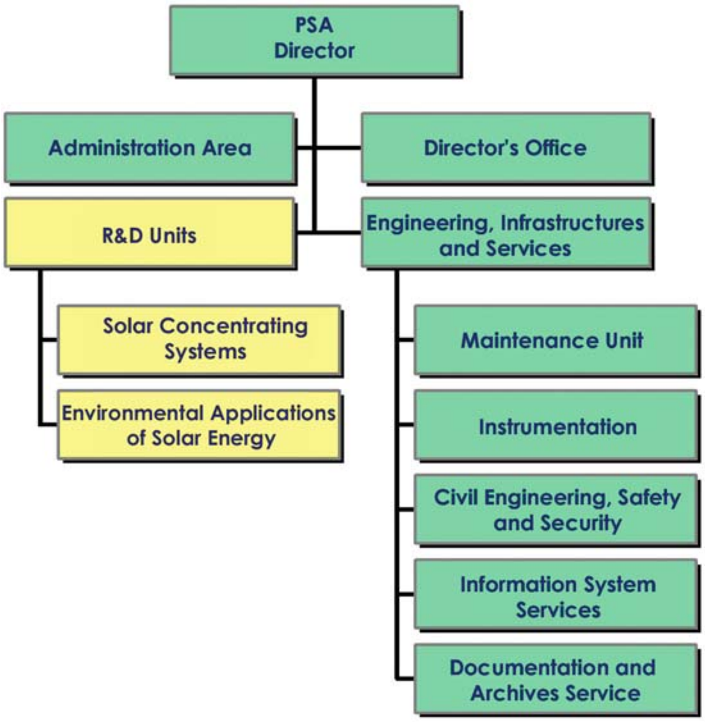


Figure 3. PSA Organization Chart for 2004. Green indicates functions and services under the Director.

Human and Economic Resources

The scientific and technical commitments of the PSA and their associated workload are undertaken by a team of 93 persons who, as of December 2004, made up the permanent staff that lends its services to the Plataforma Solar. Moreover, in addition to this permanent staff, there is a considerable influx of trainees and visiting researchers who are managed by the Director's Office.

Of the 93 persons that work daily at the PSA, an important part come from auxiliary services, operation and maintenance contracts (29 persons). The auxiliary contracts are for 8 administrative and secretarial staff 2 user information service technicians and 5 security guards. The O&M contracts are for 8 facility operators, 5 operating watchers and 13 persons for mechanical, electrical and electronic maintenance and 3 cleaners. The rest of the personnel are composed of the 37 persons on the CIEMAT-PSA staff and the 12 who make up the DLR permanent PSA delegation that result from the current commitments of

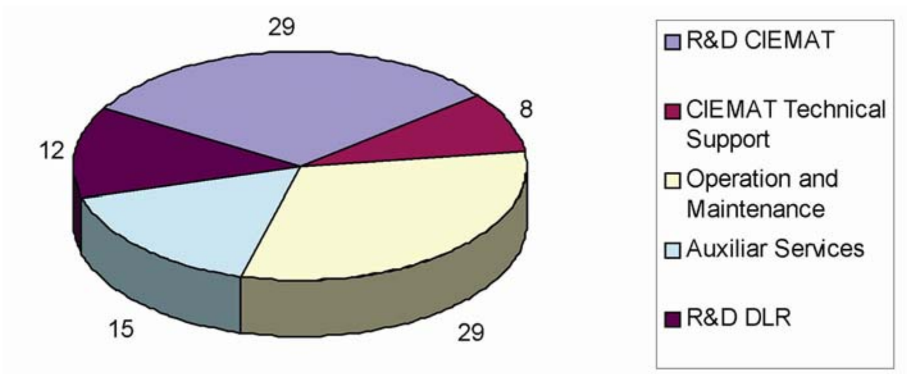


Figure 4. Distribution of PSA permanent personnel as of December 2004.

the Spanish-German Agreement.

The PSA R&D staff of 37 is still small. 24 of them are in Almería and 13, while integrated in PSA R&D projects, work at the CIEMAT in Madrid. Another 12 DLR delegation staff members also work in R&D, for a total of 49 persons devoted to R&D at the PSA.

The upward trend in the PSA budget is clear, thanks in good measure to having raised additional revenues.

Successfully raising external revenues, mainly from the European Commission, has been an outstanding contribution of our constant partner DLR. The proposal of a good number of new joint projects to the EC has allowed DLR to remain at the PSA in a new relationship based on specific projects. The fruit of this success is the relevancy of the German PSA delegation.

The number of projects funded by the National R&D Plan, where there is a growing belief in renewable energies and in particular, the concentrating solar technologies, has also increased significantly.

The PSA budget reached 5.87 million Euros in 2004 (not including the cost of R&D personnel). The CIEMAT contribution was increased to be able to undertake the activities approved in the PSA infrastructure plan. These improvements were begun in 2002 with considerable new construction, such as the new visitors building, new office building, installation of the new meteorological station, replacement of the solar furnace, repairs in the DCS field and improvements in the heliostat fields.

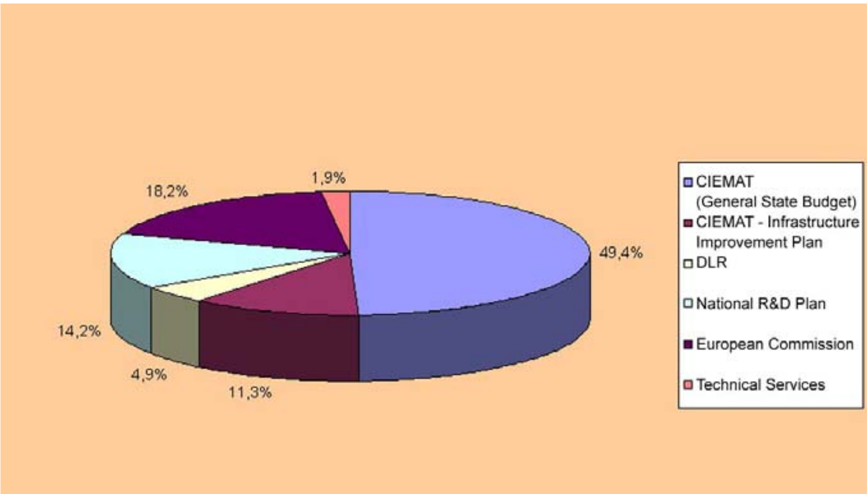


Figure 5. Distribution of Income PSA 2004

Scope of Collaboration

As mentioned above, since 1987, the Spanish-German Cooperation Agreement with the DLR, commonly known as the CHA, has been maintained at the PSA. At the present time, the relations and Annex IV of this Agreement includes a Delegation at the PSA from 2003 to 2005. This new Annex IV is being carried out to the great satisfaction of both parties.

Altogether, the scope of cooperation in which the PSA moves is very broad. In the sphere of international relations, the PSA actively participates in Tasks I, II and III of the IEA-SolarPACES program, under which information is exchanged and cost-sharing tasks are carried out with similar centers in other countries (USA, Mexico, Brazil, Germany, France, UK, Switzerland, South Africa, Israel, Russia, Australia, Algeria and Egypt).

2004 was the kickoff of the Associated European Solar Energy Laboratory (SolLAB). This virtual laboratory is made up of the major European concentrated solar energy research institutes, that is, IMP-CNRS, Odeillo (France), the solar energy division of the DLR (Germany), the Renewable Energies Laboratory of the Federal Technology Institute of Zurich (Switzerland) and the CIEMAT itself. The agreement was signed in 2004 and the coordinated tasks have already begun to give fruit, especially in the fields of flux and temperature measurement and training of pre-doctoral students. The Swiss Paul Scherrer Institute has already formally applied for membership in SolLAB.

Concerning training activities, there is an agreement for joint management of grants with the University of Almería, as well as educational agreements to receive students from universities all over Europe.

The scope of collaboration of the Mid-Temperature Solar Thermal Energy Project continues being good, since the PSA has contracts with a wide range of national and international institutions. Collaboration continued in 2004 with the Universities of Seville and Almería, with such research centers as INASMET, DLR and ZSW, the Fraunhofer Institute for Solar Energy Systems of Germany, the Weizmann Institute of Science (Israel) and the Central Laboratory of Solar Energy and New Energy Sources (Bulgaria). In industry, there are intense contacts with electric companies such as IBERDROLA, industrial firms such as SOLUCAR, GMESA and the German FLABEG Solar Int.) and engineering firms, such as the German FICHTNER and SBP, the Spanish INITEC and the French DEFY Systemes and EPSILON Ingenerie.

In the scope of 'High-Temperature Solar Thermal Energy' in the national context, there has been collaboration in projects with the SOLUCAR, SENER, IBERESE and SERLED companies and universities, such as the University of Seville, Almería, the Polytechnic University of Catalonia and the UNED. Under the umbrella of the 5th Framework Programme's Energy Programme and the Spanish-German Agreement, there has been intense collaboration with DLR in several projects and with other European institutions and companies, such as ORMAT (Israel), TUMA (Switzerland), Heron (Netherlands), FICHTNER (Germany), STC (Denmark), Forth-Cperi (Greece) and Saint Gobain Ceramics (Germany).

The new lines of research in 'solar fuels and process heat' have given rise to new cooperative projects, among them the Instituto de Tecnología Cerámica de Castellón, the Venezuelan company Petróleos de Venezuela, S.A., the Italian ENEA and the French CEA.

A strong boost in collaboration in the scope of the Chemical Applications of Solar Radiation Project has been noticed adding to the long list of institutions with which there was already collaboration in previous years. In fact, the list of current contracts includes all the possible areas, from local (Univ. of Almería, DSM Deretil, Cajamar, Coexpal, Comunidad de Regantes Cuatro Vegas), national (Grupo Abengoa, Ecosystem, Aragonesas Agro, Emuasa, Indoor Air Quality, Fundación Inasmet, Autonomous University of Barcelona, Complutense University, and the Universities of Alcalá and La Laguna, the ICP-CSIC and the Hospital of San Carlos in Madrid), European (Weir-Entropie, Ao Sol, Hellenic Saltworks, Trailigaz, Janssen Pharmaceutica N.V., Ahlstrom Paper Group, IPM, Protection des Metaux, and universities: ETH, NTUA, INETI, EPFL, Claude Bernard Lyon 1, Poitiers, L'Aquila, etc.) and outside of the European Community where there are contracts with the Mexican Institute of Water Technology (Mexico), National de Atomic Energy Commission (Argentina), National Univ. of Engineering (Perú), Tinep S.A. (Mexico), ENIG (Tunisia), Université de Fes (Morocco), Projema, S.A. (Morocco) y Photoenergy Center (Egypt).

Educational Activities

The principle governing the Plataforma Solar de Almería's Training Program is the creation of a generation of young researchers who can contribute to the deployment of solar thermal energy in all of its possible applications. Through this program, around thirty students of different nationalities are admitted every year who then contribute to the transfer of knowledge on solar thermal technology accumulated at the PSA during its twenty-five years of experiments to new generations of scientists. The main points in this training program are the following:

- Management of the grant program associated with the annual agreement with the University of Almería (UAL): PhD research and training grants
- 'Leonardo da Vinci' grants with European funding for foreign students' living expenses
- Management of the various specific educational agreements with other entities for sending students to the PSA

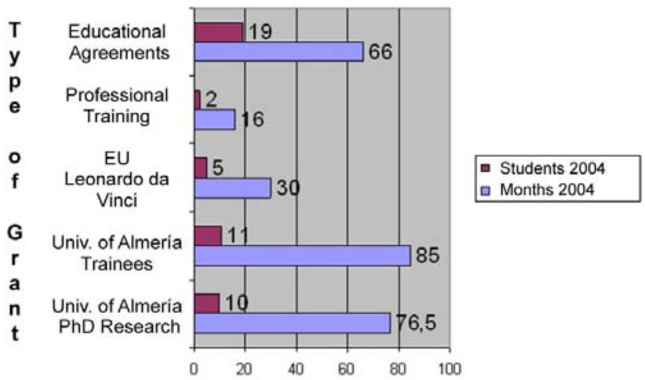


Figure 6. Student grants in 2004

Facilities and Infrastructures

General Description of the PSA

The PSA is located in southeastern Spain in the Desert of Tabernas at 37º05'27.8" north and 2º21'19" west. It receives a direct annual insolation of over 1900 kWh/(m^2·year) and the average annual temperature is around 17ºC.

The PSA's ability to offer researchers an experimental facility with climate and insolation conditions similar to those in developing solar-belt countries (where the greatest potential for solar energy is found), but with all the advantages of large scientific installations in the most advanced European countries, makes it a privileged site for evaluation, demonstration and transfer of solar technologies.

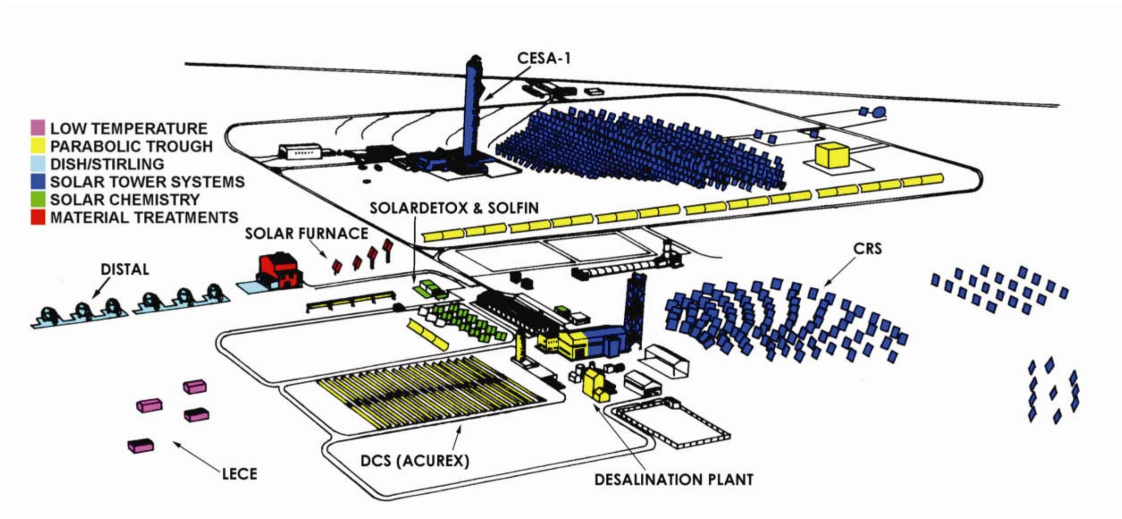


Figure 7. Location of the main PSA test facilities

At present, the main test facilities available at the PSA are [SolarPACES, 1996]:

- CESA-1 and SSPS-CRS central receiver systems, 7 and 2.7 MW_{th} respectively
- SSPS-DCS 1.2-MW_{th} parabolic-trough collector system, with associated thermal storage system and water desalination plant
- DISS 1.3-MW_{th} test loop, an excellent experimental system for two-phase flow research and direct steam generation for electricity production
- HTF test loop, a complete oil circuit for evaluation of new parabolic-trough collector components

- DISTAL dish/Stirling facility, 6 units.
- A 60-kW_t solar furnace for thermal materials treatments.
- A solar chemistry facility for solar detoxification applications consisting of a parabolic-trough loop with two-axis tracking and three CPC photoreactors for different types of trials.
- Laboratory for Energy Testing of Building Components[1] (LECE).
- Meteorological station.

Central Receiver Facilities: CESA-1 and CRS

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

7-MW_T CESA-I FACILITY

The CESA-I project, inaugurated in May 1983, was promoted by the Spanish Ministry of Industry and Energy to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the CESA-1 does not produce electricity, but 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 solar radiation high flux 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 8. Side view of the CESA-I facility with heliostat rows focusing on the medium-height test level (60 m.)

The facility collects direct solar radiation in a field of 300 39.6-m^2-surface heliostats distributed in 16 rows in a 330-x-250-m north field. The heliostats have an average nominal reflectivity of 90%, 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

[1] Laboratorio de Ensayo Energético de Componentes de la Edificación

as well as second generation units with reflective facets by ASINEL and third generation facets and prototypes developed by CIEMAT and the SOLUCAR company. In spite of its over 20 years of age, the heliostat field is in optimum working condition due to a strategic program of continual mirror facet replacement and drive mechanism repair. To the north of the field are two additional areas used as test platforms for new heliostat prototypes, one located 380 m from the tower and the other 500 away. The maximum thermal power delivered by the field onto the receiver aperture is 7 MW. At a typical design irradiance of 950 W/m^2, a peak flux of 3.3 MW/m^2 is obtained. 99% of the power is focused on a 4-m-diameter circle, 90% in a 2.8-m circle.

The 80-m-high concrete tower, which has a 100-ton load capacity, has three test levels:

- A cavity adapted for use as a solar furnace for materials testing at 45 m, which has been used very successfully in reproducing the heat ramp on space shuttles during their reentry into the atmosphere in test pieces of the ceramic shield and also for surface treatment of steels and other metal compounds.
- A cavity with a calorimetry test bed for pressurized volumetric receivers at 60 m. At the present time this cavity houses the SOLGATE project infrastructure, which includes three volumetric receivers with a total incident power of nearly 1 MW, 250-kW solarized turbine, and corresponding electric generator, air loop, heat rejection system and thermal shield.
- The 2.5-MW TSA volumetric receiver test facility at the top of the tower at 80 m.

The tower is complete with a 5-ton-capacity crane at the top and a freight elevator that can handle up to 1000-kg loads. Finally, for those tests that require electricity production, the facility has a 1.2-MW two-stage turbine in a Rankine cycle designed to operate with 520ºC 100-bar superheated steam

THE 2,7-MW$_T$ SSPS-CRS FACILITY

The SSPS-CRS plant was inaugurated as part of the International Energy Agency's SSPS project (Small Solar Power Systems) in September 1981. Originally an electricity production demonstration plant, it used a receiver cooled by liquid sodium that also acted as the thermal storage medium. At the present time, as with the CESA-I plant, it is a test facility devoted mainly to testing small solar receivers in the 200 to 350-kW$_{th}$ capacity range. The heliostat field is made up of 91 39.3-m^2 first generation Martin-Marietta units. A second field north of it has 20 52-m^2 and 65-m^2 second generation MBB and Asinel heliostats that can be used as support. The CRS heliostat field has recently been improved with the replacement of all the reflective facets, which now have a lightweight structure and low-iron glass. The most innovative feature is that in 2003, all of the heliostats were converted into completely autonomous intelligent units, communicated by radio and powered by photovoltaic energy according to the concept developed and patented by PSA researchers. At the present time, the CRS facility has the first autonomous heliostat field which does not require the use of channels or cabling thanks to the financial assistance of the Ministry of Science and Technology's PROFIT program.

The nominal average reflectivity of the field is 87%, 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 capacity of the field is 2.7 MW$_{th}$ and peak flux obtained 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 two test platforms. The first is a two-level open area at 32 and 26 m prepared for testing new receivers for chemical applications. The second is at the top, at 43 m, and houses an enclosed room with crane and calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers.

Figure 9. A CRS field heliostat reflecting the tower

Figure 10. Front view of the 200-400-kW volumetric receiver test bed in the CRS tower

The tower infrastructure is completed with a 600-kg-capacity crane and a 1000-kg-capacity rack elevator.

The test bed (Figure 10)consists of an air-recirculation circuit with axial fan and 40-kW electric heater to control the air-return temperature as well as instrumentation to measure the temperature, pressure and flow rate. Absorber outlet air is cooled by a water-cooled heat exchanger used as an indirect method of thermal balance. The calorimetric bench has been successfully employed since 1986 with logical improvements and updating, for the evaluation of all kinds of metal and ceramic volumetric absorbers.

Two PROHERMES II (Programmable Heliostat and Receiver Measuring System II) measurement systems are used to measure the flux of the concentrated solar radiation on both towers. For this, the concentrated incident solar beam is intercepted by a lambertian target, located on a plane parallel and immediately in front of the receiver aperture, at which moment a high-resolution CCD camera records the image.

After exhaustive treatment of the image (removal of electronic background noise, correction of aberrancies produced by the viewing equipment and geometric rectification), the gray-scale value associated with each pixel undergoes a transformation called calibration. This operation consists of experimentally finding a specific rule or criterion that unmistakably associates each value given the solar irradiance (W/cm^2) at a specific point on the target to a gray-scale value for the pixel corresponding to the same position previously obtained with the camera. Once the pixel map has been calibrated and the area that they represent individually on the target is found, the total power can be integrated, and the calculation of the rest of the magnitudes of interest, such as peak irradiance or distribution, is possible.

Linear focusing facilities: DCS, DISS, EUROTROUGH and LS3

The PSA has several parabolic-trough solar collector facilities. Some of them, such as the SSPS-DCS, were pioneers in Europe, while other more modern facilities, such as the DISS experimental plant, are unique and place the PSA in a privileged worldwide position for research and development of new parabolic-trough collector applications. The main characteristics of these facilities are briefly explained below.

THE DISS EXPERIMENTAL PLANT

This facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure high-temperature (100 bar/400ºC) steam in parabolic-trough collector absorber tubes. The DISS experimental plant is the only facility in the world where two-phase-flow water/steam processes in parabolic-trough collectors can be studied under real solar conditions. It is very suitable not only for the study and development of control schemes, but also for the study and optimization of the operating procedures that must be implemented in direct steam generation solar fields. Other possible applications of this plant are the study of the heat transfer coefficients in horizontal tubes through which the two-phase water/steam flow circulates, and testing of components for parabolic-trough solar collector fields with direct steam generation in the absorber tubes.

The DISS plant consists of two subsystems: the solar field of parabolic-trough collectors, and the power block. In the solar field, the feed water is preheated, evaporated and converted into superheated steam as it circulates through the absorber tubes of a 665-m-long row of parabolic-trough collectors with a total solar collecting surface of 3,838 m^2. The installation of two new collectors in 2003 has increased the nominal superheated steam flow rate that the DISS collector row can produce to 1 kg/s.

Superheated steam generated in the solar field is condensed, processed and reused again as feed water for the solar field (closed-circuit operation) in the power block.

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

Facility operation is highly flexible and can work at up to 100 bar pressure as needed (usually at 30, 60 or 100 bar) and in any of the three basic direct steam generation modes: Recirculation, Injection and Once-Through, or any combination thereof. Furthermore, it is equipped with all the instrumentation required for complete system monitoring.

Figure 12 shows a simplified diagram of the DISS loop in which the solar field is shown as one row of 13 parabolic-trough collectors with north-south-oriented rotating axes. The collectors are composed of 12-m-long by 5.76-m-wide reflective parabolic-trough modules. The solar field consists of two parts, the preheating/evaporating section and the superheating section. At the end of the preheating/evaporating section, there is a recirculation pump and a water/steam separator which augments flexibility of system operation. The

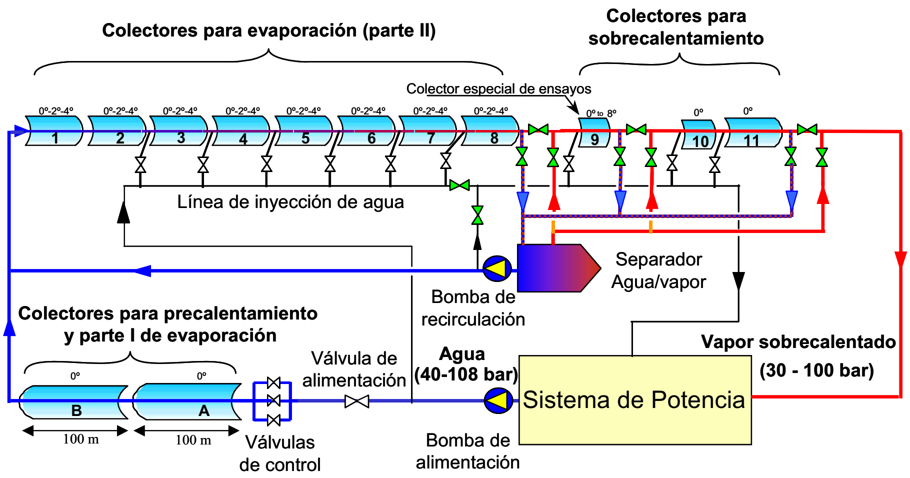


Figure 12. Simplified diagram of the PSA DISS plant

power block consists of water/steam separators, condensers, chemical dosing system, preheaters, deaerators and water pumps.

One of the most important characteristics of the DISS plant is the possibility of measuring the thermal gradient in the cross sections of the parabolic-trough solar collector absorber tubes.

THE LS-3 (HTF) TEST LOOP

The LS-3 test loop, also called the HTF test loop, which was erected in 1997, is an ideal facility for evaluating parabolic-trough collector components under real solar energy operating conditions. Mirrors, absorber tubes, solar tracking systems, etc., can be installed and evaluated in this facility, which is provided with the appropriate measurement and monitoring instrumentation.

The original facility consisted of a closed thermal oil circuit connected to a solar collector made up of four 12-m-long by 5.7-m-wide LS-3 parabolic-trough modules with a total collecting surface of 274 m^2. The thermal oil used in this facility (Syltherm 800) has a maximum working temperature of 420°C, and a freezing point of –40°C. The rotating axis of the solar collector is oriented east-west, which increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The facility's oil circuit, which has a maximum working pressure of 16 bar, is made up of the following elements:

- 1-m^3-capacity oil expansion tank, with automatic nitrogen inertization system
- 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 liters per second
- 40-kW, 3-x-380 V electric oil heater.

In the HTF test loop, and in parallel to its initial solar collector, is the EUROtrough collector prototype which was installed later. The EUROtrough collector design was developed by a European consortium which, with the financial aid of the European Commission, designed, built and erected it at the PSA and evaluated it under real conditions. The new parabolic-trough collector is apt not only for solar thermal power plants, but also for other large applications, such as desalination of seawater or industrial process heat in the 150°C-425°C range. At the conclusion of the EUROtrough project, the partners in the project donated this first prototype to CIEMAT for its operation and maintenance, and it now forms part of the PSA parabolic-trough collector facilities. With the installation of the EUROtrough HTF loop, the system's collecting area has increased to 685 m^2.

Figure 13. General view of the HTF

A thermal storage system made up of four 5-m^3, 10-15-ton modules, two concrete and two ceramic, each with a 175-kWh storage capacity, have also been inserted in the test loop for evaluation (Figure 14). They are connected in such a way that they may be charged or discharged either together or separately.

Figure 14. Storage module tube bundles

Dish/Stirling Systems: DISTAL and EUROdish

PRINCIPLES

A dish/Stirling system consists of a wide-diameter parabolic mirror with a Stirling-type external combustion motor installed in its focal area. The parabolic dish-mirror continuously tracks the sun, so that the sun's rays are reflected onto its focal plane, obtaining a Gaussian-shape concentrated solar energy map and several tens of kW. The Stirling motor is an external combustion motor that employs the thermodynamic cycle of the same name and that has two advantages that make it appropriate for this application:

- Combustion is external, that is, the energy contribution from sunlight is collected by the parabolic dish and concentrated on its focal zone.
- It is a high-performance thermodynamic cycle.

An alternator is connected to the Stirling motor so that the luminous energy can be transformed into electricity or delivered to a nearby application for direct consumption right in the same block at the focus of the concentrating dish.

The most obvious application of dish/Stirling systems is the production of electricity for self-producers in remote areas or rural communities where there is no grid, for pumping water, etc.The optimum niche on the energy market would be a power range of a few tens of kilowatts, where it would compete with the already commercial photovoltaic systems or diesel generators.

Since the beginning of activities in 1992, three generations of prototypes have been erected and routinely operated at the PSA for their technical evaluation, DISTAL I, DISTAL II and EUROdish.

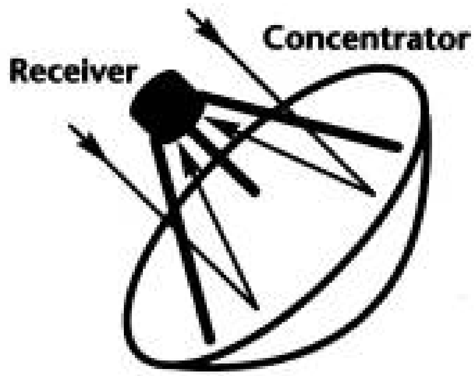


Figure 15. Schematic diagram of a parabolic dish with Stirling motor at the focus

DISTAL I

In operation since 1992, this installation initially consisted of 3 7.5-m-diameter parabolic dish units capable of collecting up to 40 kW_t energy with a SOLO V160 9-kW_e Stirling motor located in its focal zone.

The concentrator prototype was made using the stretched membrane technique, 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 meters and polar solar tracking. Two DISTAL I units were disassembled in the year 2000 and replaced by third generation EUROdish units.

Figure 16. A DISTAL I dish in operation

DISTAL II

The DISTAL II was a first attempt at a system with better features and per-kWe cost. Three new stretched-membrane prototypes were erected and put into routine operation in 1996 and 1997. Their slightly larger 8.5-m-diameter delivers 50 kW_t to the motor. The focal distance is 4.1 m and the maximum concentration is 16,000 suns at the focus. The Stirling motor, which had also evolved, is now a 10-kW_e SOLO V161 and the tracking system is azimuth-elevation, which allows automatic sunrise-to-sunset operation.

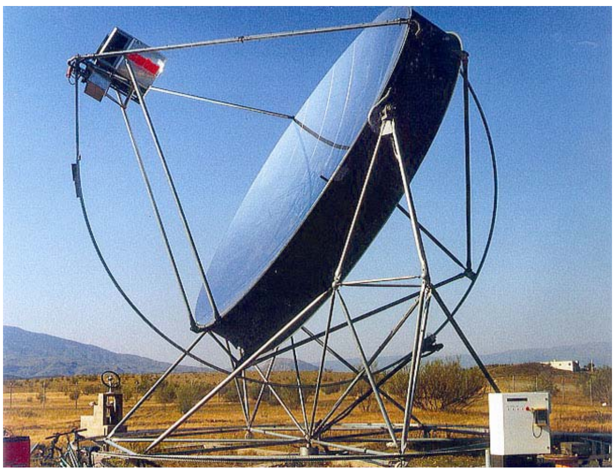


Figure 17. DISTAL II unit

EURODish

The second and latest attempt to make this technology economical is the Spanish-German EURODish project. Two new prototypes were designed and erected with the following goals:

- Reduce the price of components by using standard industrial elements.
- Develop a new dish manufacturing system discarding the stretched-membrane technology and applying a composite-material molding system.
- Develop a new optimized system assembly procedure that uses new specially developed tools.
- Remote control and monitoring over the WWW.
- Improve the Stirling SOLO V161 motor, especially those components used in the receiver cavity.
- Test pre-commercial units as reference systems.

Figure 18. Front and back views of the EURODishes.

Solar Furnace

GENERAL DESCRIPTION AND PRINCIPLES OF OPERATION

Solar furnaces reach the highest energy levels obtainable with a solar concentrating system, having attained concentrations over 10,000 suns. Their main field of application is materials testing, either in ambient conditions, controlled atmosphere or vacuum, and solar chemistry experiments using chemical reactors associated with receivers.

The solar furnace essentially consists of a continuously solar-tracking flat heliostat, a parabolic concentrator mirror, an attenuator or shutter and the test zone located in the concentrator focus [Martínez and Rodríguez, 1998].

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

HELIOSTATS

The reflective surface of the heliostats is made up multiple flat non-concentrating facets that continually track the solar disk and reflect its parallel horizontal beams onto the optical axis of the concentrator.

The PSA solar furnace has four heliostats arranged on two levels, each one of which focuses on a fourth of the concentrator, so that complete illumination of the concentrator is assured during the operating period. The heliostats have 16 3.35-m^2 sandwich-type facets, for a total of 53.58 m^2. Each one is made up of two mirrors with 90% reflectivity held to a supporting frame by 30 suction cups.

CONCENTRATOR

The concentrator disk is the main component of the solar furnace. It concentrates the incident light from the heliostat, multiplying the radiant energy in the focal zone. Its optical properties especially affect the flux distribution at the focus. It is composed of 89 spherical facets with a total surface of 98.5 m^2 and 92% reflectivity. Its focal distance is 7.45 m. The parabolic surface is achieved with spherically curved facets, distributed along five radii with different curvatures depending on their distance from the focus.

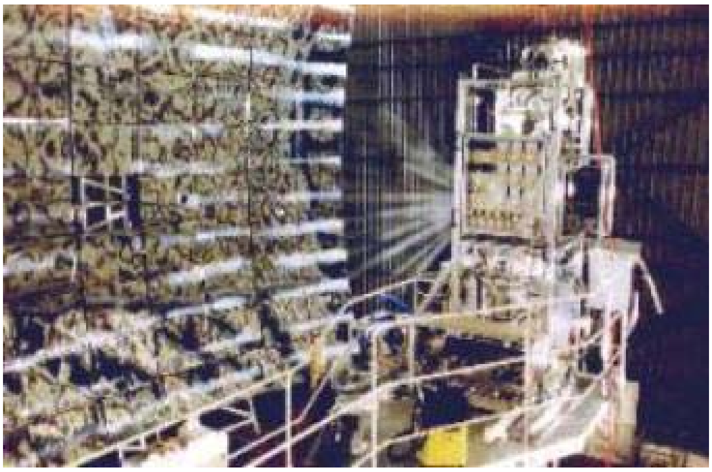


Figure 19. Solar Furnace: Concentrator (left) and receiver in operation at the focus (right).

ATTENUATOR

The attenuator consists of a set of horizontal louvers that rotate on their axes, regulating the amount of entering sunlight incident on the concentrator. The total energy on the focus is proportional to the radiation that passes through the attenuator.

It is composed of 20 louvers arranged in two columns of 15. In closed position the louvers form a 55° angle with the horizontal and 0° when open.

Figure 20. The focus and the test table on the left. On the right, the attenuator, completely open, allows the rays from the heliostats outside to enter.

TEST TABLE

This mobile support 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.

DISTRIBUTION OF THE FLUX DENSITY IN THE FOCUS

The concentration and distribution of the flux density in the focus characterize a solar furnace. This distribution usually has a Gaussian geometry and is characterized by a CCD camera hooked up to an image processor and a lambertian target. The characteristics of the focus with 100% aperture and solar radiation of 1000 W/m^2 are: peak flux, 3000 kW/m^2, total power, 58 kW and focal diameter, 23 cm [Neumann, 1994].

Solar Chemistry and Desalination Facilities

SOLAR PHOTOCHEMICAL APPLICATION FACILITIES

The first pilot plants with reactors for solar decontamination at the Plataforma Solar de Almería were developed at the beginning of the nineties (with support from the EU). The present configuration of the parabolic-trough collector photochemistry pilot plant is composed of four two-axis solar-tracking parabolic-trough solar collectors with a total collecting surface of 128 m^2. The concentrating factor achieved is 10.5 suns. Each "Heliomans" solar collector consists of a column supporting 32 mirrors in four parallel parabolic troughs for a total area of 32 m^2. The working flow rate may be varied between 500 and 4000 L/h. All the piping, tanks and accessories are HDPE (high-density polyethylene), a material highly resistant to the majority of chemicals. The module absorber tubes (56-mm-diameter, 2-mm-thick borosilicate glass) are each 16 m long, totaling 64 linear meters of photochemical reactor.

Later, other CPC (Compound Parabolic Collector) pilot plants, which can use diffuse radiation as well as direct, were installed. The CPC reflectors are made of anodized aluminum. At the PSA there are now several such plants. The oldest has three modules (1 Figure 21), each with a 3-m^2 surface tilted 37° from the horizontal, with a pump, tank and connecting piping for system operation. The total system volume is approximately 250 L and the absorber tube (illuminated volume) is 108 L. In 2002, a new 15-m^2 collector (2) connected to a recirculation pump and a tank, increased the volume to 300 L. This collector is the most advanced model developed in recent years and treatment plants to be developed in several different projects are expected to be based on it. Furthermore, two small twin prototypes (3) are also available for parallel experiments. Each reactor is made

Figure 21. General view of the CPC Solar Photochemistry Facilities with the new collector in the foreground

up of three modules of eight glass tubes each. The three modules (3.08 m^2) in each reactor are mounted on a fixed platform also tilted 37° (local latitude). The total reactor volume is 40 L, of which 22 L is the total irradiated volume and the rest is in the piping and tank.

Due to developments in the context of the European CADOX Project (see R&D Projects, Environmental Applications of Solar Energy and Characterization of Solar Radiation), a new system consisting of a new CPC-type solar collector (4) (50-mm photoreactor diameter more suitable for photo-Fenton applications) with its corresponding tank and recirculation pump (75 L) coupled to a biological reactor has been installed (150 L based on biomass attached to inert matrix) and an ozonization system (50 L, with an ozone production system of up to 15 g O_3/h). All of monitored (pH, T, ORP, O_2, flow rate, H_2O_2, O_3) and computer-controlled (pH, T, flow rate). Small prototypes (5) have also been installed for disinfection applications under the European SOLWATER and AQUACAT Projects (see R&D projects, Environmental Applications of Solar Energy and Characterization of Solar Radiation).

There are also 3 ultraviolet solar radiation sensors available, one direct with solar tracking unit and 2 global in horizontal position and tilted 37ª (same angle as the CPCs) with regard to the earth's surface. All the data are sent to a computer that stores them for later evaluation of results.

The PSA Solar Chemistry Laboratory is a 75-m^2 building designed to hold all the conventional chemical laboratory equipment: workbenches, gas extractor fan hood, storeroom for small amounts of chemicals, central distribution of technical gases, UPS, safety systems (extinguishers, shower, eyewash, etc.) precision-scale workbench, ultrapure water system, ultrasonic bath, centrifugal vacuum distillation system, as well as many other systems normally used in a chemistry laboratory. In addition, it has the following analytical equipment related to Environmental Chemistry: Liquid chromatograph (quaternary pump with automatic injector and diode detector), gas chromatograph (FID and TDC) with purge and trap system (analysis of volatiles dissolved in water), ion chromatograph, TOC analyzer (with automatic injector), UV-visible spectrophotometer, COD and BOD and automatic shredder. All these systems are completely computerized and networked. Furthermore, it has the only Andalusian network (14 stations) node in Almería for UVB/UVA/PAR measurement

SSPS-DCS PLANT WITH SOLAR DESALINATION SYSTEM

This 1.2 MW_t-capacity facility, shown in the diagram below (Figure 22), consists of four main subsystems:

- A solar field made up of 40 ACUREX 3001 parabolic-trough collectors in 10 parallel rows of 4 collectors connected in series. Its total solar collecting surface is 2,672 m^2 and the rotating axis of the collectors is oriented east-west. The fluid used by this collector field is Santotherm 55 oil, which has a maximum working temperature of 300°C. The collector absorber tubes are not evacuated and have a black chrome selective coating. It has an overall performance of 50%, with peak power of 1.3 MW_t for direct solar radiation of 950 W/m^2. The average daily thermal energy delivered is 6.5 MW_t.
- A 5-MWh_t-capacity thermal storage system consisting of a 115-m^3 inner volume thermocline oil tank for charging/discharging temperatures of 295°/25°C with automatic fire-extinguishing system, automatic venting valves and volatile-condensing system. It also has a water-cooled oil cooler for quick cooling during transient testing.
- A 500-kWe water/steam Rankine cycle electricity generating system consisting of a steam generator fed by the hot oil delivered by the solar field and/or storage tank; deaerator; steam turbine; electric generator and mechanical-draft closed-loop cooling tower.

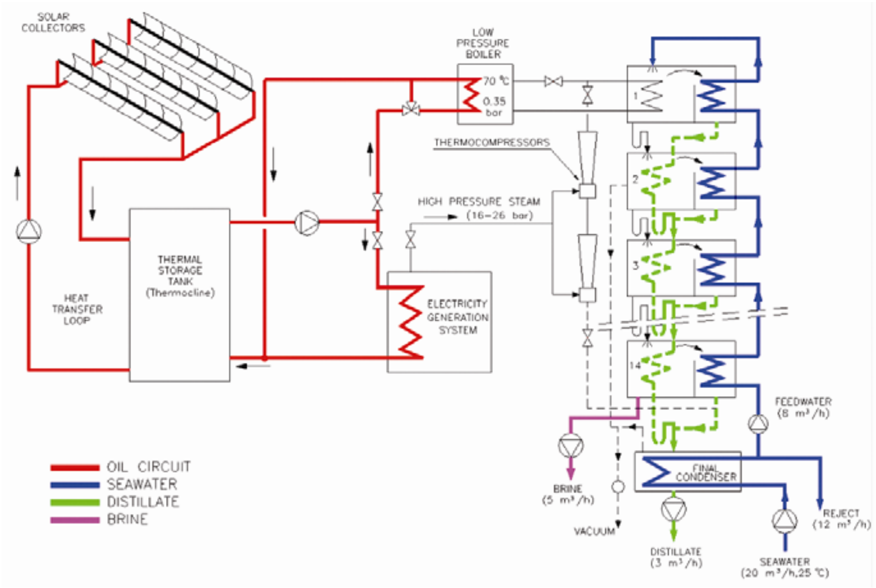


Figure 22. General diagram of the SSPS-DCS plant

- The MED desalination plant, called the SOL-14, consists of a 14-stage multi-effect distillation plant, which is connected to the thermal storage system described above. For a nominal production of 3-m³/h distillate, plant consumption is 190 kW$_t$, with an efficiency factor (number of kg of distillate produced for every 2,300 kJ of energy consumed) over 9. The saline concentration of the distillate is around 50 ppm. The nominal temperature gradient between the first and last stages is 40°C, with an operating temperature of 70°C in the first stage. The vacuum system, made up of two hydroejectors fed by seawater at 3 bar is used evacuate the air from the unit at the beginning of operation and to compensate for the small amounts of air and gas released with the feedwater, as well as any slight losses in the various connections.

A double-effect (LiBr – H_2O) absorption heat pump is the first real prototype of a device of its kind for this application. Heat loss recovery with this pump in the last condenser increases the MED plant performance ratio 20 times over operation without it.

Capacity:..................................	3 m³/hour
Number of effects:	14
Feed water:	Seawater (35,000 ppm)
Product:....................................	Distillate (≤50 ppm)
Recovery Factor:	38%
Feedwater flow rate:	8 m³/hora
Thermal consumption (FR):	63 kWh/m³ (>9)
Electricity Consumption:	3 kWh/m³
Solar field capacity:................	1.2 MWp
Solar field performance:	50%
Collector surface:....................	2762 m²
Type of collectors:	ACUREX 3001 (CCP)
Storage:....................................	5 MWh (Therminol 55)
Maximum oil temperature:.....	300°C

Figure 23. Technical specifications of the PSA SOL-14 solar desalination plant and aerial view with ACUREX field in foreground, thermal storage tank at upper left and MED upper right

STATIONARY SOLAR COLLECTOR TEST PLATFORM

This facility was erected in 2002 for the purpose of offering additional services to the scientific research community, especially energy characterization of stationary solar collectors and their possible application in solar desalination processes.

Figure 24. View of the stationary solar collector test platform

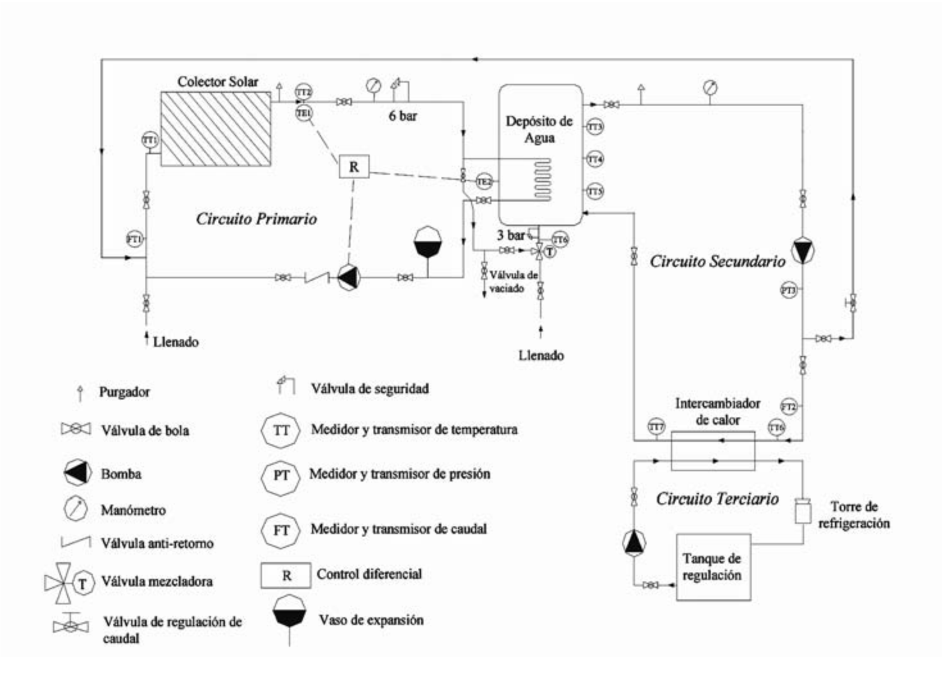


Figure 25. General diagram of the stationary solar collector test platform

GAS PHASE DETOXIFICATION LABORATORY

Different types and configurations of reactors and catalysts – flat, monolithic, tubular – are tested in gas phase in the Gas-Phase Detoxification Laboratory, located in the Renewable Energies Division in Bldg. E42 1st floor in Madrid. Any Volatile Organic Compound

(VOC) can be tested in it under controlled conditions of pollutant concentration, pressure, temperature and flow rate, of both gases and radiants and destruction efficiencies found. The energy source can be either sunlight or UV lamp, individually or combined, on different types of catalysts and reactors. It is equipped with a gas intake and mass control system, a radiation test bed with real sunlight located on the laboratory roof, and an indoor test bed with xenon lamp solar simulator. The analytical instrumentation is basically GC and GC-MS associated with a thermal desorption system, as well as continuous SO_2 and CO_2 analyzers.

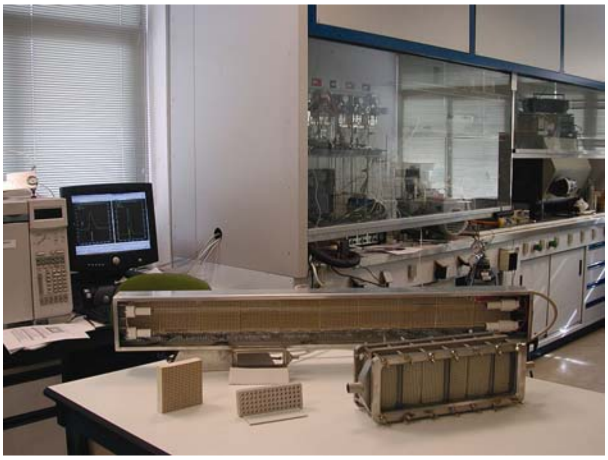


Figure 26. Different types and configurations of reactors and catalysts–flat, monolithic, tubular-tested in gas phase.

Other Facilities

PSA METEOROLOGICAL STATION

Since 1988, the PSA has had a meteorological station primarily for measuring integral solar radiation (global, direct and diffuse radiation), but also for other generic weather variables (temperature, wind speed and direction, relative humidity and atmospheric pressure, accumulated precipitation, etc.). The task of entirely remodeling this old station has recently been undertaken. Given the framework of in which our facilities work, from the beginning this initiative was intended to comply with the strictest requirements of quality and accuracy in solar radiation measurement. Furthermore, as an overall indication of having reached this goal, the new configuration of the station follows the directives of the World Meteorological Organization's Baseline Surface Radiation Network, to which the official candidacy of the new PSA radiometric station was finally admitted in 2004.

In addition to measurement of the meteorological variables mentioned, an outstanding characteristic is the measurement of the spectral distribution of solar radiation.

Figure 27. General view of the new PSA radiometric station

The instruments and equipment that make up the new radiometric station are listed below in two groups:

- Radiometric station measurement equipment
- Spectral calibration laboratory

Figure 28. Spectroradiometer probes for measuring global and diffuse radiation as installed in the solar tracker

Figure 29. Spectroradiometer detector with three-probe connector switch

The radiometric station consists of four basic parts:

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

2) *The Spectroradiometer* is so different that it must be considered an independent installation. It is a prototype developed to CIEMAT specifications by *Instrument Systems*. This equipment, based on the SP320D, which incorporates a photomultiplier and a lead sulfur detector, records the spectral distribution of the solar radiation over its whole spectral range (from 200 to 2500 nm), compared to the majority of such equipment which works only for a part of the spectrum (generally visible or ultraviolet). The basic equipment is connected to a switch in such a way that it can work with three alternating probes, which are arranged in a solar tracker to record the global, direct and diffuse solar radiation, respectively. Although it is configurable, the equipment has been programmed to record a spectrum (with an approximate resolution of 2 nm in UV and visible and 10 nm in IR) in about 7 minutes, and changes measurement probes every 10 minutes. This way we have an hourly database with 2 spectra for each one of the solar radiation variables. Another important difference from the usual solar radiation spectral distribution measurement equipment is that it operates continuously from sunup to sundown.

- Sensors on the 30-m mast:
  - 30 m: Pyrgeometer facing the ground (reflected IR)
    Pyranometer facing the ground (reflected global radiation)
    Anemometer and vane.
  - 10 m: Anemometer and vane.
    Humidity and temperature sensors
  - 2 m: Anemometer
    Humidity and temperature sensors
- Sensors on the shed roof:
  - Kipp&Zonen 2AP Solar tracker
  - Pyranometer (global radiation)
  - Shaded pyranometer (diffuse radiation)
  - Pyrheliometer
  - Absolute cavity pyrheliometer

Figure 30. View of the 30-m mast

- Instrumentation bench:
  - Pyrgeometer
  - Pluviometer
  - Barometer
  - Psychrometer
  - UVA Pyranometer

3) *The data acquisition system*. This system was specifically Developer in Visual C++ using IMP cards. Acquisition frequency is 1 s with 1-minute, hour and daily averaging. The data are stored in a relational database management system, described below, and during the acquisition a series of physical filters, among others, are applied. It is worth mentioning that this data acquisition system is connected to a GPS which also acts as a high-precision time server.

4) *The database*. The database was developed in Microsoft SQL Server 2000 and consulting tools were developed in ASP in order for it to work on the internet. The data base tables are dynamic, so it is possible to remove or add sensors to the station without having to modify the table structure. The database size has been studied to be able to have simultaneous access to 10 years of second data and averages of all the variables recorded.

The spectral calibration laboratory:

The recently acquired spectral calibration laboratory is expected to be installed in the first quarter of 2005. The need for a calibration laboratory arises from the way in which the Spectroradiometer is designed to operate. This equipment usually works only during specific measurement campaigns, in which case yearly recalibration is recommended. However, this equipment is in constant operation, and so on-site calibration is necessary to:

- Minimize loss of data during calibration periods (around 1 month if the equipment must be sent to the manufacturer).
- Be able to increase calibration frequency as needed: every six months, quarterly, monthly or even weekly.

The calibration laboratory has been specially designed for calibration over the whole 200 to 2500-nm range.

New buildings meeting the requisites for its placement had to be built to house it.

Finally, in addition to the facilities described at the PSA, in 2004, another new basic radiometric station was installed at the CIEMAT's CEDER facility in Soria. This new station will provide better solar radiation information, and also serve as a comparison with PSA measurements. It is quite similar to the one at the PSA, but with simpler equipment, consisting of a shed on the roof of which the sensors are arranged in a 2AP solar tracker:

Figure 31. New Spectral Calibration Laboratory adjacent to the CESA-1 building

Figure 32. CEDER Radiometric Station in (Soria)

- Pyranometer (global radiation)
- Shaded pyranometer (diffuse radiation)
- Pyrheliometer.
- Absolute cavity pyrheliometer

ENERGY TESTING OF BUILDING COMPONENTS LABORATORY (LECE)

The Energy Testing of Building Components Laboratory (LECE) is another of the facilities at the PSA. This laboratory is part of the Bioclimatic Architecture R&D program of CIEMAT's Renewable Energies Department and is managed directly by it. It participates in the PASLINK EEIG, a network of European laboratories with similar characteristics, which is of economic interest. The laboratory consists of four fully instrumented test cells for testing conventional and passive solar building components and, furthermore, makes use of the excellent infrastructure at the PSA for solar applications.

The purpose of the LECE is to contribute to the knowledge on the energy quality of building elements through experiments determining the thermal properties of closures, such as the global heat transfer coefficient, the solar gain factor or system response times. It also performs other types of tests among which are important because of the climatic conditions in Spain, with regard to ventilation phenomena. The knowledge of those properties can be used to improve building design for increased energy savings without loss of comfort and predicting their thermal behavior. LE high-precision time server CE activities may be classified as:

- Experimental support for preparation of standards and regulations.
- Experiments in the CIEMAT Bioclimatic Architecture R&D program.
- Collaboration with and services for building materials and component manufacturers.

Figure 33. Views of the LECE: Cells, reference buildings and solar chimney

R&D Projects

Introduction

General PSA research activity received an important boost from the new legal framework defined in Spain for solar thermal power plants based on the conditions defined in Royal Decrees 436/2004 (BOE 27/03/2004) and 2351 (BOE 24/12/2004). This new legislation has catalyzed related Spanish industrial activity. The premium of 0.18€/kWh it sets for electricity produced with solar thermal energy, along with the possibility of hybrid plants using from 12% to 15% natural gas per year, has strengthened interest of investment and industrial sectors in concentrating solar technologies. These attractive conditions have led a large number of companies to request consulting and collaboration with the PSA.

In the Mid-Temperature Solar Energy project, activities related to direct steam generation (DGS), with which it is expected to reduce solar thermal power production costs by 30%, have continued. The main nucleus of activity was the European INDITEP project, the purpose of which is the detailed design of a 5-MW_e DGS plant. The experience accumulated during years of continual DISS loop operation at the PSA will be a decisive factor for the success of this project.

Furthermore, during 2004, activities to clear up the last remaining technological unknown in the DSG process, thermal storage, were begun. The main objective of the DISTOR project, partly financed by the European Commission, is to develop a competitive thermal storage system adequate for solar plants with direct steam generation in the solar field. A storage system based on phase-change materials has been developed for this purpose.

In the 'High-Temperature Solar Thermal Energy' project, research activity has focused on the technological collaboration with companies promoting two commercial tower plants. The first, called PS10, will be the first solar thermal power plant in Spain and is due to be inaugurated in June 2006. The second initiative, called SOLAR THREE, is still in the promotion phase and it is based on the use of molten salts as the working fluid in a central receiver system.

Thermochemical hydrogen production also has its niche in the activity of this group. This year, Phase 1 of a project undertaken with Petróleos de Venezuela, S.A. and the ETH of Zurich, was satisfactorily completed. This phase consisted of studying the kinetics of the chemical process necessary for high-temperature transformation of heavy oil into hydrogen using concentrated solar energy and demonstrating its feasibility.

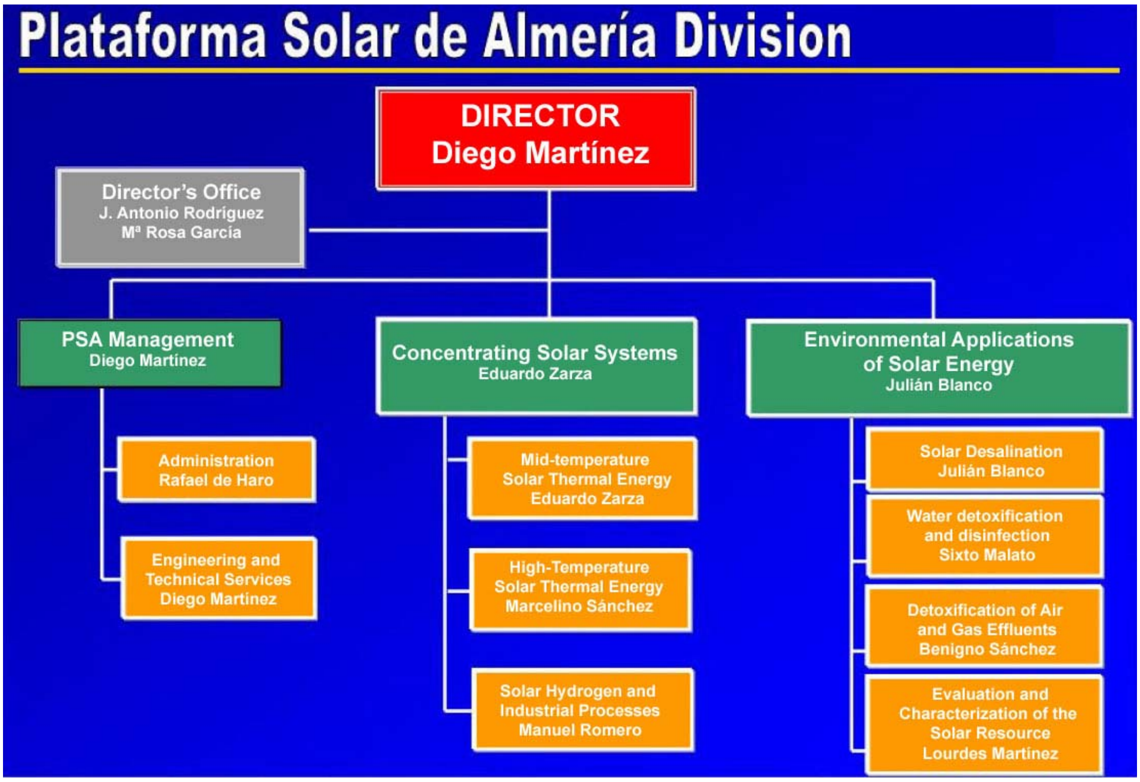


Figure 34. PSA R&D Project Organization

Our research activity in the 'Environmental Applications of Solar Energy' Project concentrated on the lines of detoxification of waste water and desalination of sea water. An important milestone was the commissioning of the first commercial solar detoxification plant in the world for the treatment of waste water from pesticide container recycling. This project is promoted by the *Albaida Recursos Naturales y Medioambiente* company and is based on scientific and technological developments at the Plataforma Solar de Almería in recent years.

High-Temperature Solar Thermal Energy

The two events that should be highlighted in 2004 because of their relevance in the organization and definition of high-temperature R&D activities at the PSA are the publication of Royal Decree 436/2004 regulating electricity production under the special regime and the internal strategic decision to unify all high-temperature research at the PSA in a single project called High-Temperature Solar Thermal Energy (ESTAT).

R.D. 436/2004 of March 12th (BOE nº75, March 27, 2004) establishing the methodology by which the legal and economic structure by which the special regime for electricity generation is updated and systematized, collects most of the scientific, technological and industrial ambitions and demands for promoting the development and commercial implantation of solar thermal power in Spain. With the approval of a tariff schedule with a premium for solar thermal power, which in practice means recognition of a sales price three times market, the basis is in place for a dynamic sector and a series of projects with active participation of the PSA that have been in the works since 1998 are finally unblocked. The interest of engineering firms in central receiver power tower and dish/Stirling technologies has been revitalized, and as a result, the PSA has become a technological tractor and center of diffusion of knowledge and experience on the subject. Two projects with central receiver power tower technology, the PS10 Project led by the SOLUCAR company which has now been relaunched, and the SOLAR TRES project promoted by SENER, will have a decisive influence in the next few years in demonstrating the maturity of these systems.

Power tower, or central receiver, systems consist of a large field of heliostats, or mirrors, that track the sun position at all times (elevation and azimuth) and direct the reflected beam onto the focus at the top of a tower. As this focus is fixed, the optics are off-axis, making their optical-energy analysis and optimization complicated. Solar concentration is on the order of 200 to 1000 times and the unit power from 10 to 50 MW, which is less than in parabolic trough plants. They may use a wide variety of thermal fluids, such as saturated steam, superheated steam, molten salt, atmospheric-pressure or pressurized air, with operating temperatures ranging from 300ºC to 1000ºC. It is a technology in which the PSA has a long research tradition at its two absolutely privileged facilities, the CESA-1 and the CRS, with very flexible test beds for component and subsystem trials and validation.

Their high incident radiation flux (usually between 300 and 1000 kW/m^2), makes it possible for such systems to work at high temperatures and be integrated in more efficient cycles, from Rankine cycles with superheated steam to Brayton cycles with gas turbines, easily admitting hybrid operation in a wide variety of options and the potential for generating electricity with high capacity factors through the use of thermal storage, and today, systems producing over 4500 equivalent hours per year are already feasible.

Central receiver systems, after concept scale-up and demonstration, is today at the gateway of commercial operation. To date, more than 10 experimental central receiver facilities have been tested around the world. Generally, they are small 0.5-10-MW systems and the most were in operation in the eighties. That experience demonstrated the technical feasibility of the concept and its ability to operate with large thermal storage systems. The most extensive experience has been in the projects developed at the Plataforma Solar de Almería and at the Solar One and Solar Two Projects in Barstow (California). Since then, technological development projects have improved components and procedures, so that today predictions set system solar-to-electric efficiencies at 23% at design point and 20% annual. In spite of all of this, the great challenge remaining for central receiver systems is getting the first generation of commercial grid-dispatch plants started under market conditions. The three technologies that are going to be used in first commercial plants are based on the use of molten salts, saturated steam and air-cooled volumetric receiver.

The high cost of capital is still an obstacle to full use of their commercial potential [Romero, Buck and Pacheco, 2002]. The first commercial applications that are on the verge of production, still have an installed power cost of 3000 Euro/kW and cost of electricity produced of around 0.18 to 0.20 Euro/kWh. A reduction in the cost of the technology is therefore essential to extend the number of commercial applications and potential sites. Aware of this, the PSA maintains a permanent line of R&D in component and system technology development to reduce costs and improve their efficiency.

Dish/Stirling systems are, without doubt the technology with the greatest long-term potential due to their high efficiency and modularity, which makes them extraordinarily attractive from the point of view of investment planning. They are small independent units with a parabolic reflector, usually connected to a Stirling motor located at the focus. Concentration is superior (1000-4000) and solar-to-electric conversion performance can be as high as 30%. The limitation insofar as its unit potential (less than 25 kW) is, however, an impediment for many large-scale electricity generation applications. Operating experience is restricted to a few units, so the technological risk is high. Reliability experience is also limited based on the accumulated hours of testing. It is also a system that requires mass production to reduce the cost of equipment, especially the motors, so investment costs in first plants are high and the uncertainty in its reduction is also high, inevitably resulting in an industrial strategy that includes exporting to a wide market to guarantee its vi-ability. The PSA harbors the widest operating and maintenance experience in these systems with over 45,000 hours accumulated in six units and it is the European test center of reference in this type of concentrator.

But 2004 has also contributed to the maturity of other high-concentrating solar device designs and system applications that break away from classical thermal power production schemes, such as development of certain industrial processes in a national project called SOLARPRO, high-concentrating photovoltaic systems, in this case a European project, HICON-PV, or the production of hydrogen from heavy hydrocarbons in collaboration with the Venezuelan oil company PDVSA and the prestigious Swiss Federal Institute of Technology (ETH) in Zurich. In addition to this range of applications, the PSA has a permanent vocation for developing better measurement tools for the testing and evaluation of high concentrating systems and components. An example in this line of activities is the MEPSOCON project, in collaboration with the Autonomous National University of Mexico, for the design, construction and characterization of a cavity calorimeter for measuring concentrated radiation flux in solar concentrating systems.

To optimize available capacities, facilities and human resources, to attend the growing demand for outside collaboration more efficiently in a wide range of applications, in January 2004, a strategy concentrating all of them in a single internal research project, ESTAT, was initiated. This project incorporates the facilities, capacities and resources of the old Central Receiver Technology Project and part of those corresponding to the Training and Access project, in particular the activities and developments linked to the parabolic dish and solar furnace technologies.

The goal of this new line of R&D is to develop knowledge, technologies and applications in the scope of high-temperature, high- photon-concentrating solar energy. This includes the following specific objectives:

- Development of more efficient, more economical high-temperature, high concentrating solar components and systems, especially those with the greatest weight in the total plant cost (concentrator, receiver, thermal storage), and simplification of associated O&M through greater automation.
- Improve knowledge in basic disciplines, develop tools, methodologies, procedures, codes and instrumentation, and reference test facilities, both for internal core research in solar high concentration and for their application in industrial projects.
- Foster development and consolidation of an industrial sector through technology transfer, feasibility studies, R&D roadmaps and definition of action tending to eliminate non-technological barriers that impede penetration of this technology.
- Optimize integration of solar concentrating devices in more efficient electrical conversion systems and schemes, in both thermodynamic cycles and direct conversion systems.
- Characterize optical and thermal properties, as well as the reliability of materials used in high-concentrating, high-temperature solar technologies.
- Develop materials surface treatment and sintering technologies using high photon concentration and high temperatures.
- Develop solar thermochemical production technologies for hydrogen and other solar fuels, evaluating solar fuels and solarization of high-temperature industrial processes

The internal program of work of the ESTAT project is articulated in three general lines of research as shown in Figure 35:

1) High-concentrating solar components and systems
2) Materials and instrumentation technology
3) Solar fuels and industrial processes

The research activities carried out by the PSA ESTAT group in 2004 concentrated on the following specific projects, all of them financed by public R&D programs.

High-concentrating solar components and systems.

1) Project: "ECOSTAR: European Concentrated Solar Thermal Roadmap". Ref. 502578. Announcement: Energy1- Sustainable Energy Systems – 6th FP. Financing entity: EC-DG Research). Participants: CIEMAT (Spain), DLR, VGB (Germany), CNRS (France), WIS (Israel), IVTAN (Russia), ETH (Switzerland). Coordinator: R. Pitz-Paal (DLR). CIEMAT Senior Researcher: M. Romero. Period: December 2003-April 2005.
2) Project: "PS10: 10 MW Solar Thermal Power Plant for Southern Spain"; Ref. NNE5-1999-00356. Announcement: 1999/C 77/13. Financing entity: EC-DG TREN (ENERGIE Programme). Senior Researcher: Rafael Osuna (SOLUCAR). Participants: CIEMAT, SOLUCAR (Spain), DLR, Fichtner (RFA). Period: July 2001-July 2004.
3) Project: SOLPRO-II – Promotion of a Solar Thermal Power Plant with a 2.8-GWh Annual Electricity Generating Capacity (1.5 MW power) in Almería. Ref. FIT-120000-2004-93. PROFIT 2004 announcement, Ministry of Education and Science. Senior Researcher: V. Fernández (SOLUCAR). Participants: CIEMAT, CENTER and SOLUCAR. Period: January 2004-June 2005.
4) Project "SOLAR TRES: Molten Salt Solar Thermal Power 15 MWe Demonstration Plant"; Ref. NNE5/369/2001. EC-DG TREN (ENERGIE Programme). GHERSA, SENER, CIEMAT (Spain), Saint Gobain (France), Boeing (USA), Alstom (Czech Republic). Period: December 2002-December 2007.
5) Project: "HICONPV: High Concentration PV Power System". Ref. 502626. Announcement: Energy1- Sustainable Energy Systems – 6th FP. Financing entity: EC DG Research). Participants: Solúcar Energía (Coordinator), DLR, Fraunhofer ISE, PSE, CIEMAT, RWE, Ben Gurion University, EDF, University of Malta. Senior Researcher CIEMAT: M. Sánchez. Period: December 2003-December 2006.
6) Project: "SOLAIR: Advanced Solar Volumetric Air Receiver for Commercial Solar Tower power plants"; Ref. NNE5-1999-10012 Announcement: 1999/C 77/13. Financing entity: EC- DG TRAIN (ENERGIE Programme). Participants: CIEMAT, SOLUCAR, IBERESE (Spain), STC (Denmark), DLR (Germany) and FORTH/CEPRI (Greece). Senior Researcher: R. Osuna (SOLUCAR). Period: February 2000-June 2004.
7) Project: "HST: Hocheffiziente Solarturm-Technologie – High efficiency solar tower technology: BMU-German Ministry of the Environment 1001 and Kreditanstalt für Wiederaufbau-KfW. Participants: CIEMAT (Spain), DLR, KAM, G+H, Isolite (Germany). Coordinator: R. Buck (DLR). Period: January 2002-September 2004.

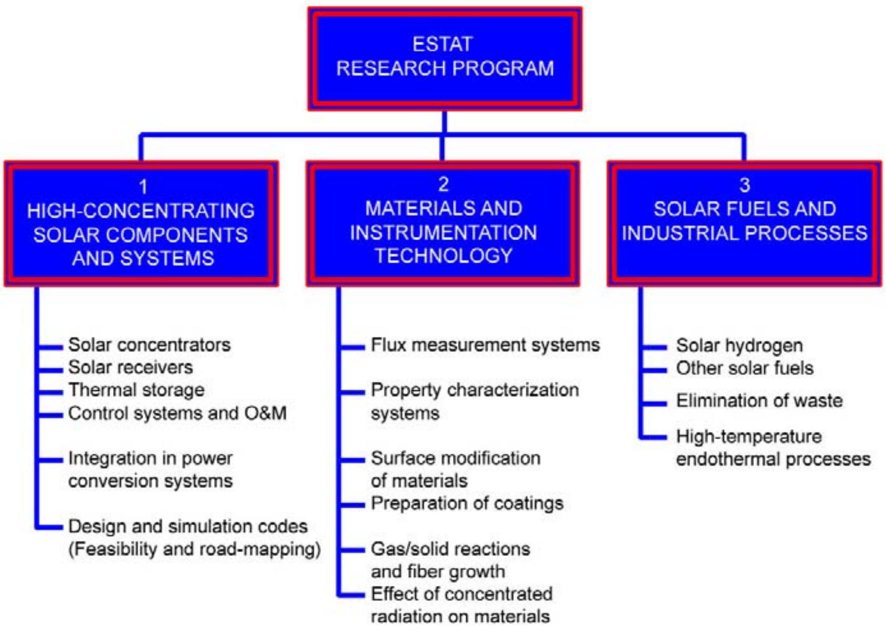


Figure 35. The solar thermal high-temperature (ESTAT) project structure grouped by subject

8) Project: "Megahelio – Large-Reflective-Surface Heliostat Tracking System for Solar Thermal Power Plants" Ref. FIT-120102-2002-19. PROFIT-2003 Announcement, Ministry of Science and Technology. Senior Researcher: J. Enrile (SOLUCAR). Participants: CIEMAT and SOLUCAR. Period: (January 2003-April 2004).
9) Project: "Space-Cil Heliostato Cilíndrico para Plantas Termosolares". Ref. FIT-120100-2003-62. PROFIT-2003 Announcement, Ministry of Science and Technology. Senior Researcher: V. Fernández (SOLUCAR). Participants: CIEMAT and SOLUCAR. Period: (January 2003-April 2004).
10) Project: "PCHA: First stand-alone heliostat field-Phase II"; Ref. FIT-120100-2003-54. PROFIT-2003 Announcement, Ministry of Science and Technology. Senior Researcher: G. García (CIEMAT). Participants: CIEMAT (January 2002-April 2004).
11) Project: "The Monocentric Solar Concentrator: Search for a Competitive Modular Alternative". Ref. FIT -120100-2003-47. PROFIT-2003 Announcement, Ministry of Science and Technology. Senior Researcher: M. Sánchez (CIEMAT). Participants: CIEMAT. Period: (January 2003-December 2004).
12) Project: "Development of Control Tools and Systems for Solar Thermal Power Plants". Specific collaboration agreement between the CIEMAT and the University of Almería. Senior Researchers: Manuel Romero (CIEMAT) and M. Berenguel (UAL). Period: Nov 2002-October 2005.

Materials technology and high flux instrumentation

1) Project: "MEPSOCON: Concentrated Solar Power Measurement in Central Receiver Power Plants". Ref. DPI2003-03788. Announcement: National R&D Plan 2002, Industrial Production Program. Ministry of Science and Technology. Senior researcher: J. Ballestrín (CIEMAT). Participants: CIEMAT. Period: December 2003 - December 2006.
2) Project: "SolarPRO: Development System of Process Heat from Concentrated Solar Radiation: Testing and Characterization of its Application to Various Production Processes and Elimination of Waste at High Temperatures". Ref. REN2003-09247-C04-XX/TECNO. Announcement: National R&D Plan 2002, Environment program. Ministry of Science and Technology. Senior Researcher: D. Martínez (CIEMAT). Participants: CIEMAT, ITC, Univ. Seville, UPC. Period: November 2003 - November 2006.

Solar fuels and solarization of industrial processes.

1) Proyect: "INNOHYP: Innovative Medium-Long Term Routes for Hydrogen Production – Coordinated Action". Ref. 513550. Announcement: Energy1- Sustainable Energy Systems – 6th FP. Financing entity: EC-DG Research). Participants: CEA (France), DLR (Germany), ENEA (Italy), USFD (UK), EA and CIEMAT (Spain), CSIRO (Australia), JRC (Netherlands). Coordinator: F. Le Naour (CEA). Senior Researcher CIEMAT: M. Romero. Period: June 2004-July 2006.
2) Project: SOLTE-R-H: "Hydrogen Generation from High-Temperature Solar Thermal Energy". Ref. FIT-120000-2004-66. PROFIT-2004 Announcement, Ministry of Education and Science. Senior Researcher: J. Brey (Hynergreen). Participants: CIEMAT and Hynergreen. Period: (January 2004-April 2005).
3) Project: "Solar Thermochemical Application for Production of Syngas+H2 from Heavy Crude Oil". Specific Collaboration Agreement between PDVSA (Venezuela), ETH (Switzerland) and CIEMAT (Spain). Senior Researcher: J. C. de Jesús (PDVSA), A. Steinfeld (ETH), M. Romero (CIEMAT). Period: January 2003-June 2007.

HIGH-CONCENTRATING SOLAR COMPONENTS AND SYSTEMS.

This more consolidated line of research inherits goals and resources from the old Central Receiver Systems project. The main groups of activities are shown in Figure 36. Among the wide range of projects are feasibility studies and participation in demonstration projects that require the active contribution of the PSA for technology transfer and commercial implementation of high-temperature solar systems, without abandoning participation in projects with new innovative schemes, development of specific components, such as solar receivers, solar concentrators, control systems and perfection of design and simulation tools.

Figure 36 clearly shows how those activities closest to commercial plant applications, feasibility studies and development of new production schemes, receive financing from the EC, while heliostat and solar concentrator development are financed by national plans and by collaboration with industry. Finally, those subjects most related to the improvement of capabilities or tools are funded by CIEMAT.

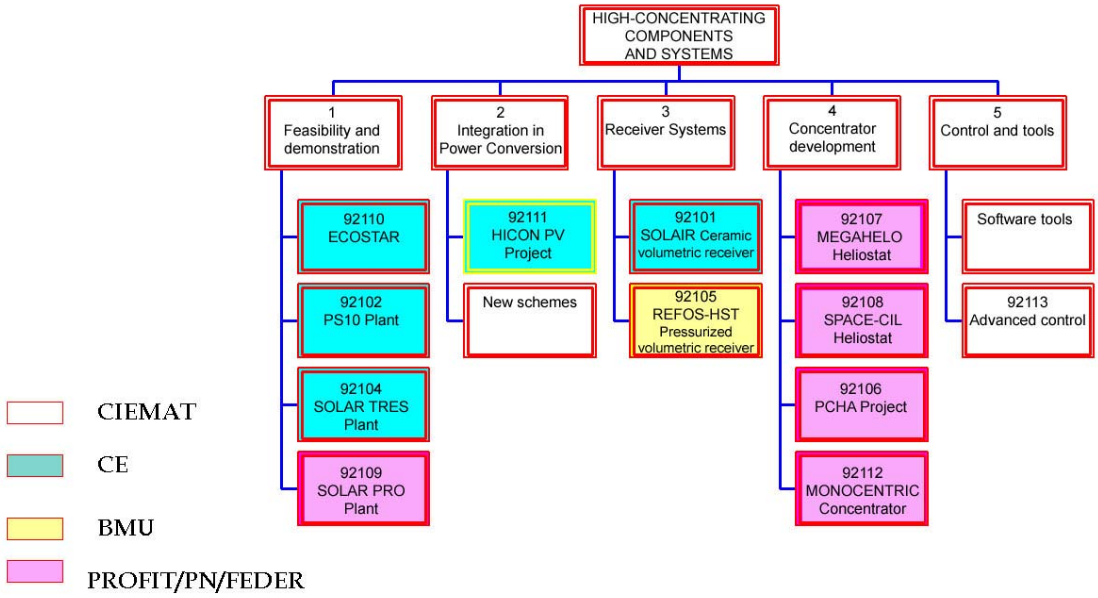


Figure 36. Grouping of Components and High-Concentrating Solar System R&D projects. Color denotes source of funding.

The ECOSTAR Project:

The purpose of this short project was to design a concentrating solar thermal power generation technology roadmap. Work was coordinated by DLR (German Aerospace Center) with the participation of the major European solar concentrating technology research and development centers (CIEMAT, ETH, IVTAN, WIS, CNRS), and consulting from the European Electricity Producers Association (VGB). Specifically, the study concentrated on determining the technical innovations with the most impact on penetration by solar thermal power systems.

The methodology for analysis selected seven typologies of reference plants (SEGS-type parabolic trough, direct steam generation parabolic trough, water/steam power tower plants, power towers with molten salt, power towers with air-cooled volumetric receiver, hybrid power tower with pressurized volumetric receiver, and dish/Stirling Systems). The comparison was carried out for a typical 50-MW plant adapted to each of the technologies employing the average cost of electricity production (LEC or Levelized Electricity Cost) as the parameter for comparison.

As may be observed in Figure 37, a 60% reduction in LEC is expected by a 2020 horizon, this being almost half the cost of introducing innovative technologies. In all cases, these reductions in cost are achieved through a combination of three or more technological innovations such as increased size, use of new materials and structures in solar concentrators, integration of storage systems and advanced solar receivers and implementation of more efficient thermodynamic cycles. The current design most optimized for cost would be based on the power tower with molten salt, in the mid-term, it would be water/steam

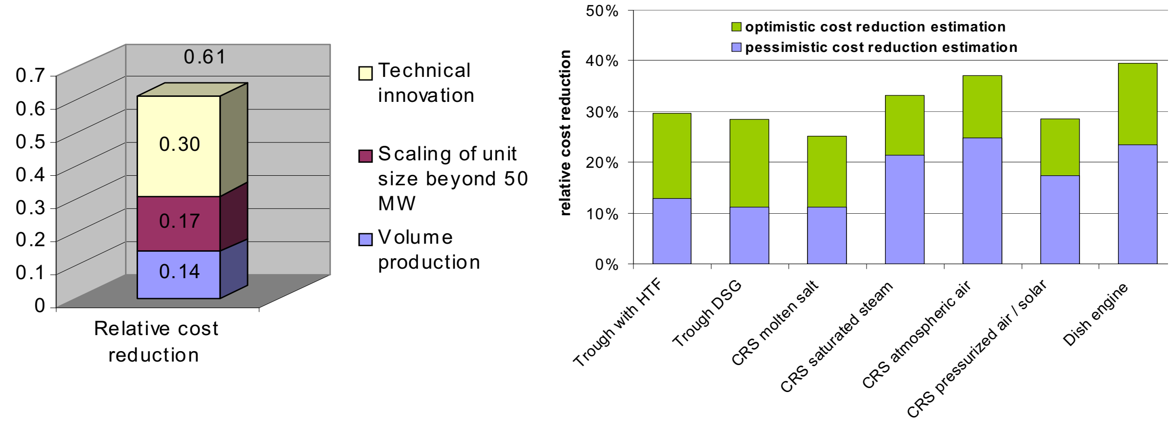


Figure 37. Influence of technological innovation on cost reduction in different solar thermal power systems

systems, both parabolic trough and tower, and finally, systems based on volumetric air receivers, where a longer road must be covered for efficiency and cost optimization.

Commercial demonstration projects: PS10, SOLPRO and SOLAR TRES

The PS10 project, begun in 1999, has had a long history up to now and awakens numerous expectations in the solar community as the first commercial solar power tower initiative inside and outside of our country. For the PSA, the PS10 project is enormously important, since it is the obligatory reference that enables research and development in central receiver technologies to be focused and feedback to be channeled between industry, in this case the SOLUCAR company, and a public research agency such as the CIEMAT, enabling joint strategies to be defined in heliostat development, advanced concentrators, solar receivers, software codes and tools, and thermal storage, which are the generators of many projects that have been financed by the Ministry of Education and Science PROFIT program.

The main objective of the PS10 Project (Planta Solar 10), also known as Sanlúcar Solar, is the design, construction and commercial operation of a solar thermal power tower plant with heliostat field and rated power of 11 MW. This plant is being installed in the municipal limits of Sanlúcar la Mayor, in the province of Seville, and it is due to be inaugurated in 2006. The plant is being promoted by Abengoa through its operating company, Sanlúcar Solar, and coordinated by SOLUCAR. The project has received a subsidy of five million Euros from the European Commission and 1.2 million Euros from the Andalusian Regional Government. CIEMAT, DLR and Fichtner Solar are partners in the European project.

The project was originally based on the Phoebus scheme, which used pressurized atmospheric air as the thermal fluid and a volumetric solar receiver. In 2003, the technical project was completely revised. The initial requirements set by the promoter at the beginning of the project, 3000€/kW and annual production of 24 GW annual production for a first small-size commercial plant turned out to be difficult to reach with the air technology. Based on these limitations, the basic scheme was modified, and the plant now has a saturated-steam solar receiver. The system has a metal-glass heliostat (Sanlúcar-120 heliostat), field, a saturated steam cavity receiver, thermal storage and saturated steam turbine.

The system will use a total of 624 121-m² heliostats developed by the SOLUCAR company and a 100-m-high tower. A cavity solar receiver, selected to reduce radiative and convective losses, achieves 92% thermal efficiency. The absorber panel is made of individual flexible vertical tubes to absorb thermal expansion and mechanical deformation without breaking or leaking. The receiver produces 40 bar/250°C saturated steam, which is fed to a boiler that increases system thermal inertia. The power block works with 250°C saturated steam and rated conversion efficiency of 30.7%. The system thermal efficiency at design point is estimated at 21.7% with an annual average of 16.3%. In this sense, the

(Courtesy of SOLUCAR)

Figure 38. Aerial view of the PS10 plant during construction

challenge of finding the simplest and most economic technology that still improves efficiency has been achieved.

For cloudy periods, or solar transients, the plant is provided with a 15-MWh saturated steam storage system that permits 50 minutes of turbine operation at 50% load.

The PSA collaborated with SOLUCAR in project definition, mostly review of TECNICAL's new solar receiver design, definition of a direct flux measurement system inside the cavity, validation of the heliostat field optimization procedure (by comparison between the SOLVER and STC codes) and evaluation of the Sanlúcar-120 heliostat.

With all of this, the PS10 project is only a first step that would logically be followed by development of a plant with a second cavity for superheated steam. The scheme, which consists of the use of central towers with a double cavity (one for saturated steam and another for superheated steam), has been analyzed in the PROFIT project called SOLPRO. The SOLPRO scheme has been retained by SOLUCAR for its future implementation in new water/steam plants.

It must be mentioned that participation in commercial demonstration projects also relaunched the SOLAR TRES project in 2004. This project is promoted by the SENER company for the purpose of developing and building a 17-MW plant based on the molten-salt cooling technology. In 2004, some very important steps were taken in project revitalization, such as renegotiation of the European Commission subsidy of 5 million Euros, the development of a specific heliostat by SENER that has been tested at the PSA, and startup of a technology development agreement with CIEMAT for developing a new solar receiver concept to be tested at the Plataforma Solar de Almería. The SOLAR TRES project bases its profitability on the use of a large thermal storage system, equivalent to 15 hours at full load, which would allow continuous 24-hour operation in summer.

New production schemes: The HICON-PV project

Integration of thermal energy collected in the solar receiver into more efficient electricity generation schemes is an ongoing line of research at the PSA. This approach is carried out through both the search for options or power production schemes based on the most advanced thermodynamic cycles and incorporation of electricity generation systems by direct conversion (photovoltaic, MHD, thermomionics, etc.).

The purpose of the HiConPV project (High Concentration PV Power System) is to develop, manufacture and test a photovoltaic concentration device able to work with solar radiation fluxes of 1000 kW/m^2. The HiConPV project is financed by the European Commission 6th Framework Programme under priority 6.1.3.2.3: Advanced renewable technology concepts-PV concentration. The project began in February 2004 with a kickoff meeting organized by the PSA in Almería. The participants are Solúcar Energía (Coordinator), DLR, Fraunhofer ISE, PSE, CIEMAT, RWE, Ben Gurion University, EDF and University of Malta. The final aim of HiconPV is to develop a concentrating photovoltaic technology for a system cost of 1€/W$_p$ by 2015. On one hand, the project selects solar concentrating systems adequate for high-concentration photovoltaics, and their adaptation to the strict requirements of radiation flux and temperature distribution on the PV module. This task is entrusted to CIEMAT and DLR, with the collaboration of PSE in defining the cell cooling system. Insofar as the photovoltaic solar receiver, the most visible technological challenge in the project is design of an integrated monolithic module (IMM) and construction of a solar receiver based on compact modules composed of these IMM, for which the Fraunhofer ISE is responsible. The Si cells are limited to concentration factors under 500x and to module efficiencies of 20%, so the HiconPV proposal is based on the use of GaAs cells that allow high flux and provide better efficiencies. Multi-junction cells can reach efficiencies of 35%, although HiconPV concentrates on a first stage where the module will use cells with only one junction. The target set by ISE for 2004 was to achieve several 17x25-mm IMM prototypes. These IMM will be tested in the DLR solar furnace in Germany, the PSA solar furnace in Almería and the Ben Gurion solar dish in Israel.

In 2004, PSA activity in the HiconPV project focused on optical simulation and optimization of several types of solar concentrators, such as parabolic dishes, Fresnel and central towers. In particular, an optics design option identified the use of a modified spherical concentrator that permits smoother concentrated solar flux profiles admissible by the PV module to be obtained. The PSA has also devoted a considerable effort to the solar furnace infrastructure necessary for IMM and PV compact module testing and characterization, including an advanced a quick shade system, modification of the control system, instrumentation and heat reject system.

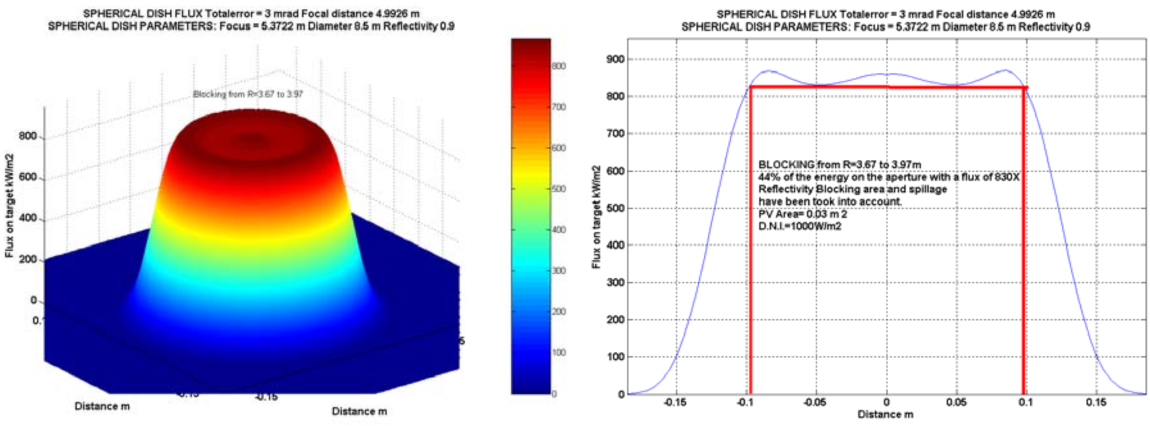


Figure 39. Flux profile obtained with an 8.5-m-diameter modified spherical concentrator with 3-mrad total error at a focal distance of 5 m. The smooth profile is ensured in a 10-cm-diameter focal region.

Volumetric receivers: SOLAIR and HST Projects

The receiver is the genuine nucleus of any power tower system, and is the most technologically complex component, because of the need to absorb the incident radiation with the least loss and very strict concentrated flux conditions. Among the various thermal fluid options and heat exchange options, the PSA has been concentrating its research on developing air-cooled volumetric solar receivers since 1986. Volumetric receivers are specifically conceived to optimize heat exchange with air as the thermal fluid, the absorber

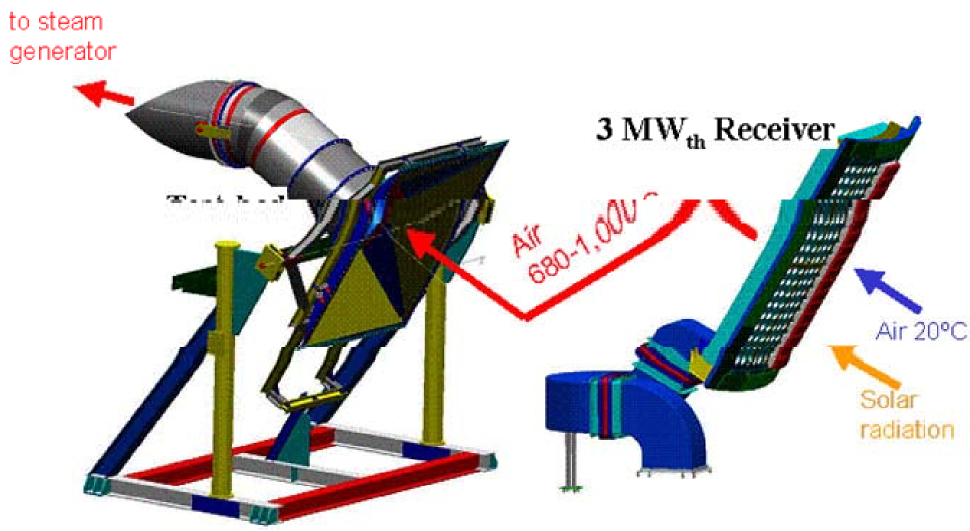


Figure 40. SOLAIR-3000 test bed flow diagram showing the main components and input solar radiation

illuminated being a porous matrix or medium (knit metal or ceramic monolith), through which the cooling gas flows.

The purpose of the SOLAIR project is to achieve a volumetric air receiver with an SiC ceramic absorber able to produce hot air at 700°C, with a modular concept easily scalable to large plants. The use of a ceramic matrix provides improved absorber durability and its design in modular cups eliminates the fluid-dynamic instability of previous designs. Finally, it incorporates a new air recirculation system that allows recirculation ratios of approximately 70% to be reached. The SOLAIR project is a European EC-financed project in which the CIEMAT, SOLUCAR and IBERESE (Spain), HelioTech (Denmark), DLR (Germany) and CPERI (Greece) are participating. The CIEMAT has a very active role in this project, leading prototype testing and evaluation, performing analyses and optimizing the hot air recirculation system with fluid dynamics codes such as FLUENT®, selecting the geometry of the ceramic heads and performing thermomechanical structural analyses using the ANSYS® code.

The SOLAIR project started in 2000 and finished in June 2004, having completed its last test campaign with a 3-MW prototype receiver installed in the TSA test bed, located at 80 m of the PSA CESA-I tower.

Testing had to be interrupted several times due to partial breakage and ungluing of some of the ceramic cups on the SiC absorber. The incidents were explained by deficient bonding in some parts of the cup/absorber sets. The SOLAIR project ended in July 2004, after a total of 150 hours of useful on-sun operation. The partners therefore decided to extend testing to the end of 2004 in order to be able to accumulate more operating experience. 188 tests were performed with solar flux measurement at outlet air temperatures of 600, 650, 700 and 750°C, at full and half loads. The thermal efficiency obtained is shown in Figure 41, where it can be seen that it is very sensitive to power and temperature. For a nominal target power of 3 MW, 72% efficiency was obtained, varying between 70 and 75% for nominal operating temperature of 750°C and flux of 370-520 kW/m^2. In applications that require somewhat lower air temperatures (of around 600°C) efficiencies over 85% are obtained.

The most outstanding characteristic of the Solair-3000 design is that it is completely modular. Its modular configuration was conceived so that the 3-MW test module can be replicated dozens of times to form a cluster on the receiver of a commercial plant. Its attractive concept and the 3-MW receiver tested motivated the European Commission to select the SOLAIR project as one of the three renewable energy reference projects in the

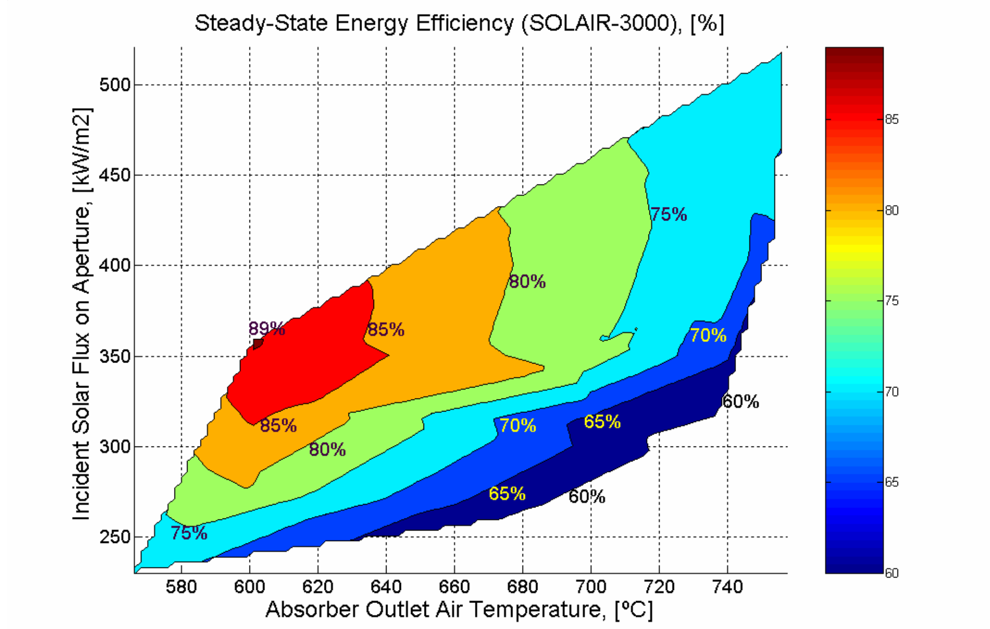


Figure 41. SOLAIR-3000 volumetric air receiver efficiency as a function of incident solar flux and outlet air temperature

5th Framework Energy Programme presented to European communications media in March 2004.

The SOLAIR receiver is open to the atmosphere and, therefore, produces hot air at atmospheric pressure. In this case, the reference use is integration in a Rankine superheated steam cycle through heat exchange in a steam generator. Another option is a second line of longer-term research in which the solar receiver is integrated in a Brayton cycle with gas turbine using pressurized volumetric receivers. The basic objective of this alternative is hybrid solar-gas turbine plants. Hybrid solar thermal plants have great potential for up to a 30% cost reduction over solar-only plants.

A great step forward in this line of research was represented by the SOLGATE project. The SOLGATE project was the first successful initiative in connection with a pressurized volumetric solar receiver with combustion turbine. SOLGATE received EC financing and, apart from the DLR and the CIEMAT, ORMAT (Israel), SOLUCAR (Spain) and TUMA (Switzerland) took part in it.

The system includes the combination of a 250-kW turbine with a 1-kW receiver cluster, made up of three modules connected in series. The Ormat OST3 turbine has been adapted to receive air preheated in the solar receiver so it can operate in hybrid mode (solar-fossil) or in fossil-only mode. The SOLGATE project demonstrated the technical feasibility of integration and was able to operate the solar cluster, supplying hot air at over 900ºC which was injected into the turbine combustion chamber. Now that the SOLGATE project is completed, the new test campaign, with a new ceramic receiver, is included in the HST (Hocheffiziente Solarturm-Technologie – High-Efficiency Solar Tower Technology) project, financed by the German BMU and among the objectives of which is to improve system efficiency by including a new high-temperature ceramic solar receiver that will reach an air outlet temperature of 1100ºC. The CIEMAT participates in this project, coordinated by the DLR, the 2004 objective of which was integration of the new ceramic absorber (Figure 42) and operation and testing with the OST3 turbine at higher temperatures. Once the new receiver and its instrumentation and associated peripherals had been installed and adjusted, testing was done in June, July and August 2004. During testing, some overheating was found in certain areas of the quartz window due to defective cooling of the window and that prevented the system from reaching 1100ºC as intended. In the month of August, the operating test maximum was 1030ºC. At 100ºC, the solar receiver sur-

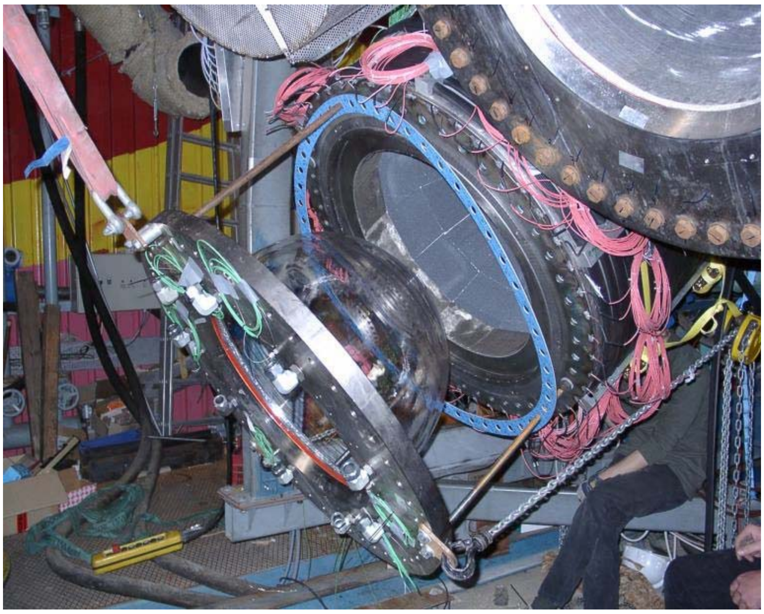


Figure 42. Detail of the new 1100ºC ceramic absorber, connection to instrumentation and quartz window during erection

passed 75% thermal efficiency. Based on the results obtained, it may be concluded that the system is technical feasible operating at 1000ºC and 6 bar, the application of which is of great interest to cogeneration and distributed power generation systems.

Heliostats and solar concentrators

The Sanlúcar-120 heliostat represents the most mature, commercial reference to date. SOLUCAR estimates place its cost at under 180€/m^2 for production of about a thousand units (150€/m^2 with improvements in the current actuator mechanism.) This objective has, however, to be backed by execution of the PS10 project.

In 2003 and beginning of 2004, the PSA carried out two projects financed by PROFIT funds, also in collaboration with SOLUCAR, for successive improvements in production costs. Arising out of that collaboration were the Megahelio and Space-Cil designs. The conceptual study of a monocentric concentrator, which was able to reach high temperatures and concentrations using a static concentrator and a mobile cylindrical solar receiver, was also developed during this period. The purpose of the Megahelio project was to develop a new prototype heliostat tracker with a useful surface of around 200 m^2 for solar thermal plants, which improves the reference cost of the Sanlúcar-120 heliostat by up to 30%.

The optimum technical-economic configuration insofar as distribution of mirrors is like the one in the picture below (Figure 43). A total of 48 3220-mm-x-1355-mm mirrors make up a total net reflecting area of 209.43 m^2, but the total surface exposed to the wind is larger, about 215 m^2. The support structure has a horizontal metal trussed beam (in blue) almost 26 meters long. Another innovative aspect of the design is its support on two pedestals, one of them fixed and the other with movement on a semi-circular rail. Although the Megahelio design achieved the estimated cost target of less than 180€/m^2, with a potential for reduction of 30% over this reference price, these objects also seem reachable by the Sanlúcar-120 heliostat, based on possible improvements in the actuator mechanism. Therefore, it was decided not to continue into the prototype construction and testing phase.

One of the objectives pursued in recent years at the PSA is evaluation of the technical-economic feasibility of the use of intelligent stand-alone units. These heliostats have integral photovoltaic panels for an autonomous power supply for the control system and solar

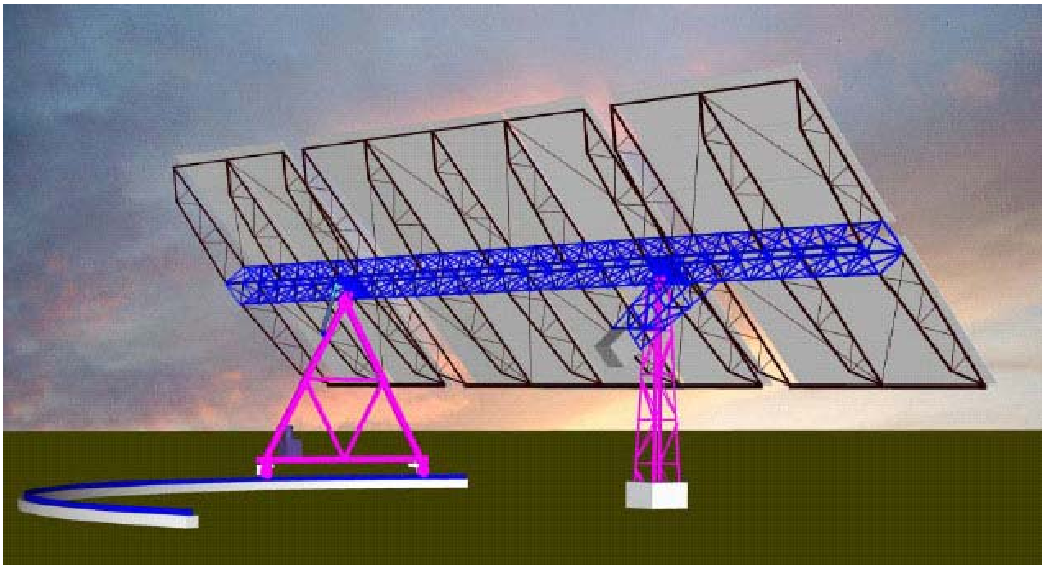


Figure 43. Artist's view of the 200-m² Megahelio heliostat (Designed by SOLUCAR)

tracking actuators and a wireless communication system to govern the heliostat field, during both routine, emergency and safety operation. This stand-alone concept has been patented by the PSA. The stand-alone concept implies that this heliostat, equipped with a specially designed local control, can operate without the assistance of any external device, and can, by itself, perform the functions of calculating and guiding its axis, keeping the focus controlled, as well as watching out for its own integrity and safety. It will be able to perform its functions alone or, as will usually be the case, as a component of a central tower heliostat field. The main characteristic of the stand-alone heliostat is that it can be installed anyplace without the usual electrical wiring and/or channel infrastructure. By using photovoltaic energy to supply each heliostat independently and wireless communication by radio over commercial channels, the stand-alone concept takes on its greatest importance in an important innovation, which can be applied successfully in heliostat fields in future solar power tower plants, in an attempt to cheapen the costs of civil engineering work by eliminating the network of channels and power, signal and communications wiring.

Figure 44. Partial front view of the PSA CRS heliostat field, which has 92 fully autonomous radio-controlled units. In the center of the heliostat, at the top of the pedestal, the PV panel supplying power to the control system and the antenna for communications with the control center.

After several trials with prototypes and mini-series of autonomous heliostats, the PSA has set a world stand-alone milestone by putting the whole CRS field of 92 radio-controlled heliostats in operation. The PCHA project (First Stand-Alone Heliostat Field), begun in 2002, at a total cost of 650,000€, was partly subsidized by the Spanish Ministry of Education and Science PROFIT program. The third and last phase of the project, completing field erection begun in October 2003, was carried out in 2004. In March 2004, the entire field was put into operation and the long-range test plan was begun. The first evaluation campaign was performed in September 2004 and included communications, operating and power consumption tests. A comparative study with conventional heliostats, using the PS10 plant field of 624 heliostats in Seville as a reference, was also carried out. Communications tests with a total of five central radiomodems in the CRS field, enabled communication at a rate of 20 heliostats per second and refreshed the entire field every five seconds, demonstrating the feasibility of communications. With this solution, a communications scheme could be proposed for the PS10 field that enables the field to be refreshed every 10 seconds. The failure rate obtained was less than 0.4%. Operating tests demonstrated that the high-wind protection system and, in general, self-protection mechanisms essential in a stand-alone heliostat, worked well. At the end of 2004, over 7000 hours of operation had been accumulated. Electricity consumption was extraordinarily low, with an average of 129 W_h/day in an operating mode requiring 12 hours of solar tracking. In fact, one of the main conclusions is that the PV system was clearly oversized, even causing some overload problems, so a 30 Wp panel is more than sufficient. The PV power system's use of diffuse radiation leads to enormous self-sufficiency, and there were no power supply problems, even in winter under adverse weather conditions. The extrapolation of these data to a large 120-m^2 commercial heliostat, such as the one to be used in the PS10, results in a daily total of 341 W_h, of which 221 W_h would be consumed by motors, the rest of fixed electronics consumption and losses. For a 120-m^2 heliostat the optimum system would consist of a 110 Wp panel and a 100 Ah battery. A comparison of extrapolated data for large-sized stand-alone heliostats and a conventional field the size of the PS10 shows a 55% potential cost reduction, even with periodic replacement of batteries during plant lifetime. We therefore believe that the PCHA experience was completely satisfactory and demonstrated not only the technical, but also economic benefits of stand-alone heliostat fields in commercial plants.

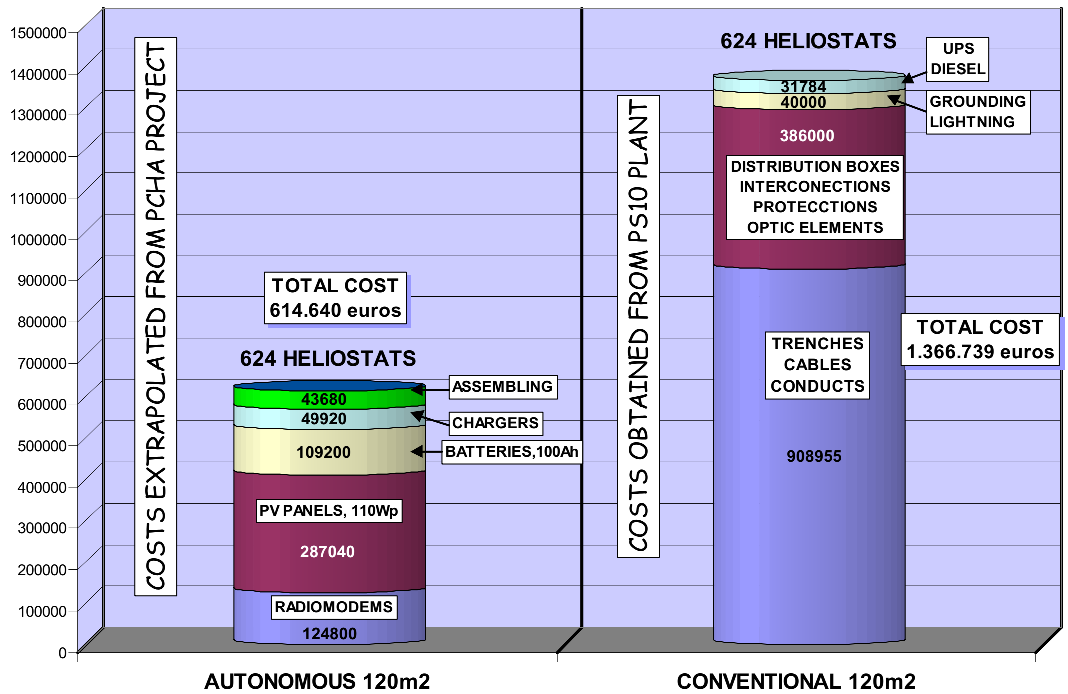


Figure 45. Cost comparison of stand-alone and conventional heliostat fields for 624 120-m^2 units (Data based on the PS10 field)

Development of Advanced Control Systems (UAL)

A fruitful line of collaboration in control system development is maintained with the University of Almería (UAL) based on a scientific cooperation agreement signed in 2002. Under this agreement, considerable research work has been done in cooperation with the Automation, Electronics and Robotics Group at the University of Almería. This agreement includes the development of a new real-time heliostat field control system to be implemented in the PSA CESA-1 and CRS fields and integration of control environments, data acquisition systems and evaluation of power tower receiver test results.

In 2004, a significant advance was made in control systems for both the CESA and CRS control fields. It should be emphasized that for the development of software for these control systems, technologies that not only offer a local solution for the PSA heliostat field control, but are scalable solutions adaptable to commercial power tower plants. Specifically, they are using standardized distributed objects technologies in which temporal determinism in software component behavior is guaranteed by use of Real Time Operating Systems (RTOS). In the environment of this project, CORBA® on LynxOS® is being used to develop control systems for both heliostat fields. Concerning integration of control environments, acquisition and solar receiver test results, a Control System for the Receiver Block, Storage and Air Circuit has been designed and developed based on LabView®. This system will be perfectly integrated with the Heliostat Field Control System and other CIEMAT telematic network computers (in the PSA and CIEMAT-Moncloa subnetworks to provide a real-time environment for analysis of the experiments performed at the PSA. This environment was already used satisfactorily in the last SOLAIR project tests.

One of the most relevant developments in 2004 was the dynamic model for the CESA-1 plant Receiver/Storage Air Circuit system. Just as for the Solar Furnace dynamic model, this was done with object oriented modeling technologies using the Dymola /Modelica® tools. Development of this type of models is required to optimize control algorithms for the facility. Figure 46 presents a diagram of this model in which the different power plant components (solar receiver, storage tank, heat exchanger, water pump, etc.) can be seen. The main system components were modeled in the Thermofluid environment. System dynamic behavior in response to a cloud transient has been simulated.

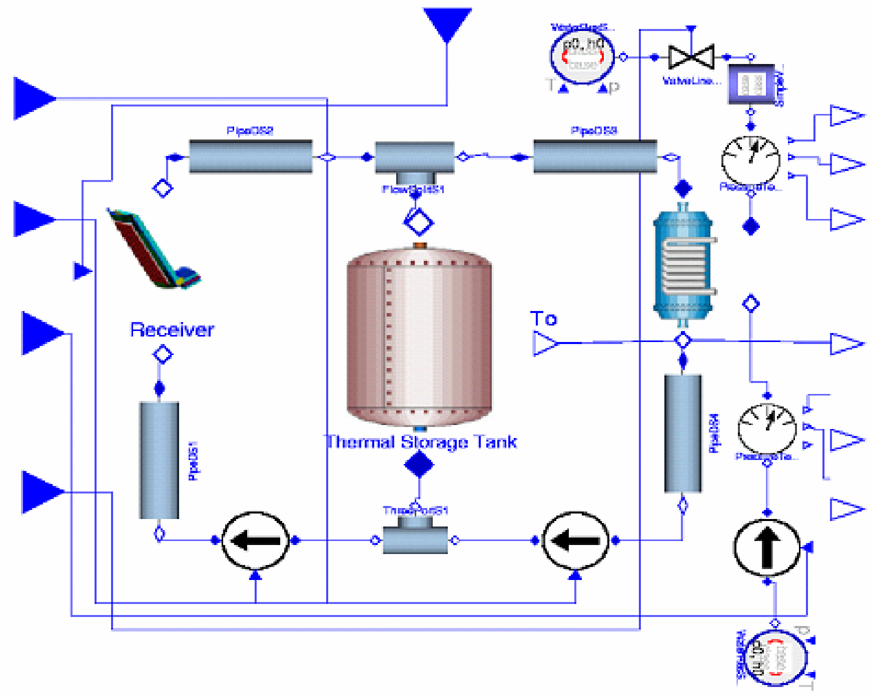


Figure 46. Dynamic model with Dymola/Modelica® of the TSA/Solair facility with volumetric air receiver, thermal storage, steam generator and blowers

MATERIALS TECHNOLOGY AND HIGH FLUX INSTRUMENTATION

The activities included in this section are considered fundamental to a center of excellence in testing and measurement of solar concentrating systems such as the PSA. In particular, the search for more reliable concentrated solar flux measurement methods and instruments and testing and preparation of materials subjected to high flux, are essential for coming generations of plants. If these activities are usually permanent at any scientific solar concentration facility of reference, they are mostly overlooked because they are buried in component development projects or systems testing. They are therefore characterized by their markedly horizontal profile. There are, however, projects financed by the National Plan for R&D that concentrate their specific objectives on developing these techniques and processes. In 2004, this activity was undertaken in the MEPSOCON and SOLARPRO projects.

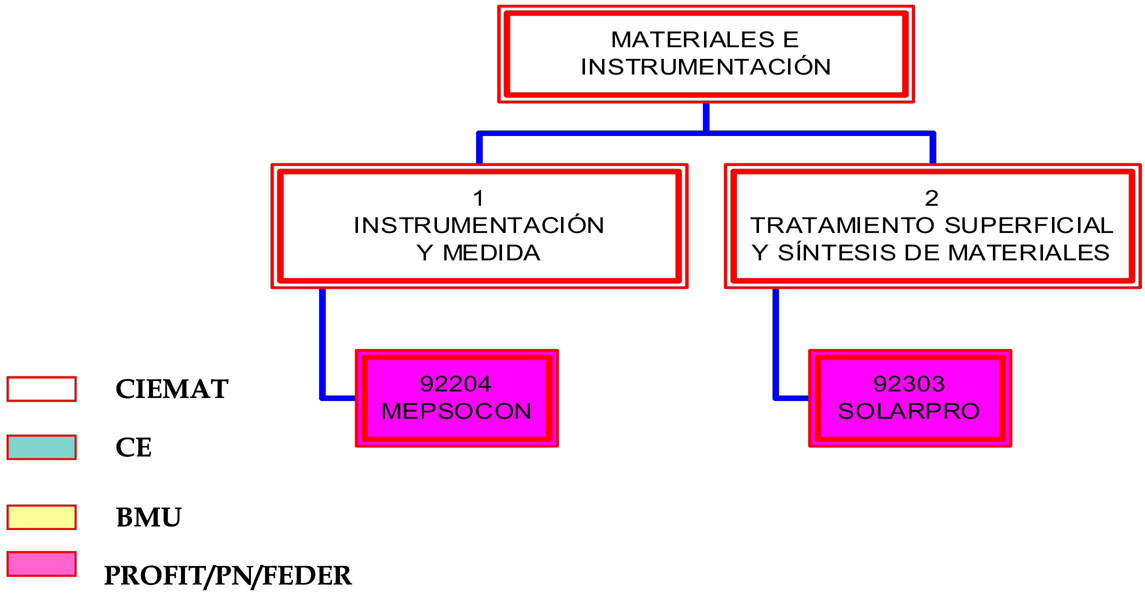


Figure 47. R&D projects in the line of materials, instrumentation and measurement. Color shows the source of funding

Instrumentation and measurement (MEPSOCON Project)

Many factors affect the measurement of concentrated solar radiation and make it necessary to improve precision. This uncertainty is passed on to the final solar plant design and consequently, to its price. Therefore, the different causes that distort measurement of the incident power must be analyzed to significantly reduce that uncertainty. The definition of a calibration procedure for the sensors (calorimeters) used in measuring highly concentrated solar radiation and the design of a new calorimeter that mitigates the deficiencies of current devices are the main objectives of a new project called MEPSOCON: "Measurement of concentrated solar power in central receiver power plants". The MEPSOCON project, financed by the National R&D program through its Industrial Design and Production Program, began on December 1, 2003 and ends on November 30, 2006. MEPSOCON and the development of radiometers and calorimeters is the purpose of collaboration with the Energy Research Center of the Autonomous National University of Mexico, which has among its objectives, the construction and characterization of a cavity calorimeter for the measurement of concentrated radiation flux in concerning solar systems.

The characterization methods employed use a Gardon radiometer, for which a specific calibration procedure with a dual-cylinder graphite cavity black body as a reference, has been established, following the procedures of the NIST (National Institute of Standards and Technology). When the calibration procedures for the Gardon radiometer had been es-

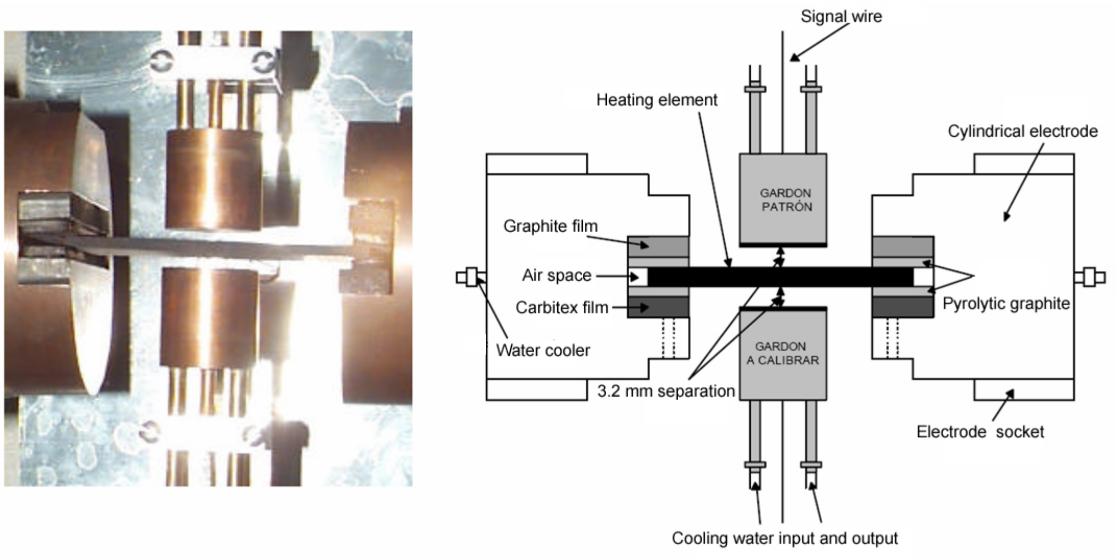


Figure 48. Photo and diagram of the position of the heating element and sensors for calibration

tablished, a systematic error was found (Type B uncertainty) in its use for the measurement of solar radiation. This uncertainty is dependent on the coating of the radiometer. If the coating is Zynolyte, the radiometer overestimates the measurement by 3.6%, and if the coating is colloidal graphite, it overestimates it by 27.9%. These systematic errors are the result of the spectral radiance of a black box at the calibration temperature (850ºC) is significantly different from the spectral distribution of solar radiation, the maximum of which by the Wien law of displacement is at 2580 nm. Therefore, there is a systematic error in the power absorbed by the coatings at the two different spectral distributions. This systematic error was recognized by the Vatell Corp., which jointly published the finding, of great relevance for extensive use of these radiometers in solar applications. In order to use these sensors for solar radiation measurement, a correction by an adimensional factor of 0.965 must be made to the calibration constants for Zynolyte and 0.782 for colloidal graphite.

Surface treatment and materials synthesis (SOLARPRO Project)

The adaptation of the solar concentrating technology to intensive endothermic industrial processes requiring high temperatures and a significant reduction in CO_2 are a clear objective of solar energy. Advancement in the knowledge of the use of concentrated solar radiation for surface treatment and synthesis of materials is also of great importance, for which tools like the solar furnace are essential. The purpose of the SOLARPRO project is to demonstrate the technological feasibility of using solar thermal energy as a system of energy input in industrial processes other than electricity production having high temperature as their common denominator. The experience and knowledge acquired in central receiver technology projects is combined with that of materials treatment activities carried out in the solar furnace, which was perfected for this purpose in 2004.

For this project, the processes to be studied are basically classified into two groups:

1) Industrial production processes: Since it is intended to make use of the capacity for generating the high temperatures typical of solar concentrating systems, a study on the feasibility of its application to processes in the ceramic industry and sintering of metals is proposed.
2) Waste treatment processes: An innovative line approaching the elimination and recovery of heavy metals from contaminated soils is proposed.

The members in the SOLARPRO project are:

- Department of Mechanical and Materials Engineering, University of Seville (USE). Knowledge of the metal sintering process.

- Institute of Ceramics Technology (Castellón) (ITC). Technological center with knowledge of ceramics industry manufacturing processes.
- Department of Fluid Mechanics, Polytechnic University of Catalonia (UPC). Knowledge of the problem of soils polluted by heavy metals.

The processes initially selected for study are the following:

- Typical ceramics industry processes:
  1. Drying of 'raw' pieces before firing (100°C < T < 200°C)
  2. Drying by atomization (200°C < T < 350°C)
  3. 'Third firing', for certain types of glazing (800°C < T < 900°C)
  4. 'Frits' (1400°C < T < 1600°C)
- Metallic composite sintering processes in a reductive atmosphere. (T~ 1000°C)
- Processes for eliminating metals in polluted soils. (Hg, T~ 630°C)

The main objectives of the Project are:

- Demonstrate the technological feasibility of the concept.
- Acquire enough data and experience to optimize the solar energy equipment design and operating procedures to the applications tested.

- Process modeling and validation with real data.

  - Identify potential new solar energy processes.
  - Arrive at conclusions that aid in scaling up the system to around a megawatt power

In 2004, the solar furnace was perfected for the SOLARPRO Project, for which a test bed for heating air with a volumetric solar receiver to be applied in Subprojects 1 and 2 (drying of industrial ceramic pieces and sintering of powdered metallurgical materials, particularly copper). A second reactor has been developed based on the rotary solar furnace concept and will be used in Subproject 3 (heat recovery of soil polluted by metals, particularly mercury.)

Testing in the Solar Furnace

Operation of the Solar Furnace was mainly devoted to testing in the projects called "Own Lines" of research of the PSA Materials Group, such as the Solarpro project, which, in collaboration with the Instituto de Tecnología Cerámica (ITC) of Castellón has performed tests to obtain frits from different mixtures of powdered alumina and zirconia, and with the School of Mining Engineering of Madrid, has tested foaming of aluminum test pieces. Also in the "Own Lines" of projects are the tests performed with the CIEMAT Department of Fusion in which compacted aluminum test pieces were treated at very high temperatures. Automatic attenuator control tests were also carried out in collaboration with the University of Almería and furnace flux was measured with a calorimeter designed and fabricated by the Autonomous University of Mexico in the National R&D Program Project, MEPSOCON.

Other Improvement of Human Potential (IHP) program tests which began in 2003 with the ARC Research Center, Seibersdorf, in collaboration with the Technical University of Riga, and could not be completed due to Furnace infrastructure problems, were completed in 2004.

In the framework of the INTAS program with the University of BMSTU of Moscow, an alumina insulating material was also tested at very high temperatures.

The **Seibersdorf ARC Research Center** and the **Technical University of Riga** are involved in development of nanomaterials from powdered refractory compounds. Traditional sintering methods are related to an intense grain growth associated with physical and mechanical properties undesirable in the consolidated ceramics.

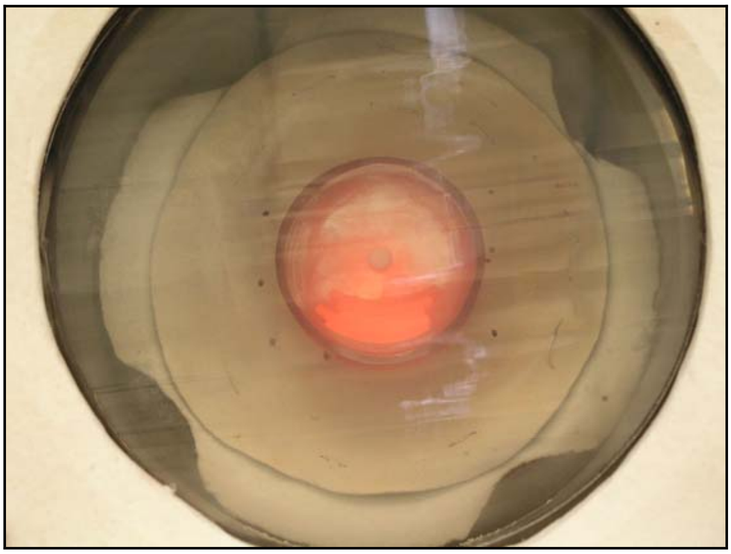


Figure 49. MiniVac test crucible

Sintering by plasma and related techniques such as sintering by electrical pulses, are quick, energy efficient and highly effective, producing very dense fine-grain materials.

Sintering in the Solar Furnace is an alternative way of fast sintering. The combination of fast heating, short processing period and quick cooling, make these techniques a powerful tool for materials development and micro-structural optimization.

In testing performed by the PSA Materials Group in collaboration with the institutions mentioned above, different TiCN, WC and W test pieces were treated in the Mini Vacuum Chamber (MiniVac) in the Solar Furnace in an stream of N_2 at temperatures between 1500 and 1750ºC.

The purpose of the test campaign carried out in the framework of the INTAS program with the **Bauman Moscow State Technical University –BMSTU-** in association with the German **ASTRIUM GmbH** company, is the "Development of Numerical and Experimental Research Methods in Heat Transfer in Porous Thermal Protection Materials".

This Project is intended to generalize and systematize the results of research in different thermal porous material protection systems, and develop algorithms to identify heat transfer parameters from experimental data obtained in the tests, using reverse problem solving methods.

Figure 50. Concentrator and test area during testing

Porous thermal insulation materials are widely used in engineering, for example, they are essential protection elements in spacecraft, such as the Space Shuttle (USA) or the Buran rocket (Russia), for reentry into the atmosphere.

Several different flux density experiments were performed, beginning with the lowest densities and gradually increasing to the maximum density with the attenuator 100% open, at 150 and 1900 kW/m² and temperatures between 700 and 1900°C.

The MEPSOCON program flux measurement tests, were performed with a calorimeter called the Cavical fabricated by the University of Mexico, which, by making use of the difference in water temperature at the calorimeter inlet and outlet, enables the energy entering the calorimeter to be calculated indirectly.

Two test campaigns were performed at different attenuator apertures to find the different energy levels in the furnace at different positions between 0% and 100% open.

Characterization of the Solar Furnace Focus

Testing for characterization of the Solar Furnace focus at the end of September merits special mention, since once the four original MBB heliostats had been replaced by a single heliostat, the new flux distribution on the focal plane had to be found.

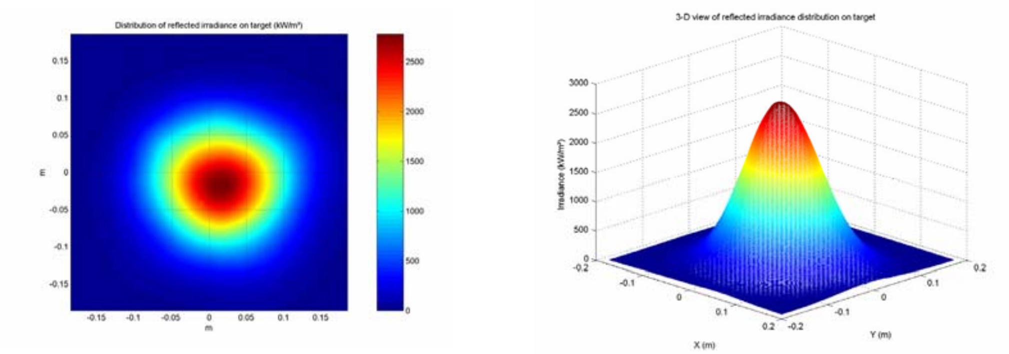
The new, 140-m² heliostat, called the GM-140, was fabricated by Solucar.

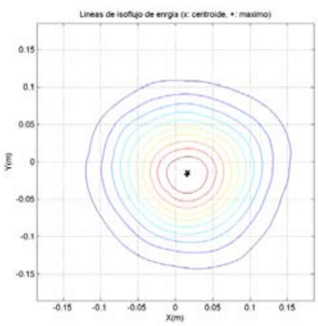
To measure the flux, the Furance's lambertian target was used with a HYCAL radiometer having a range of 3.4 MW/m². Images were taken with the new Hamamatshu C4480 CCD camera connected to a Pentium 4 computer with Image Pro Plus software by Media Cybernetics.

For characterization, 17 measurements were taken for each one of the attenuator apertures, at distances between +150 and -150 mm from the focal plane in 10-mm steps. The attenuator apertures used were between 20% and 100% in 10% intervals. The total power measured was 70 kW with a radius of 13 cm for 90% of the energy on the focal plane.

FACILITY IMPROVEMENT

The new control and data acquisition software, conceived as a SCADA (Supervisory





Power information on Solar Furnace Target
Total Power .... = 70 kW
Peak Irradiance .... = 3051 kW/m²
Statistic analysis of Irradiance distribution:
Slant Range........................ = 7.440 m
Centroid location................ = (0.016,-0.014) m
Peak location...................... = (0.016,-0.017) m
90-Percent Energy Radius..... = 0.130 m
Maximum rms-radius............ = 0.062 m
Minimum rms-radius............. = 0.058 m
Ellipticity............................ = 1.07
Ellipticity direction............... = 182.3 °

Figure 51. Flux measured on the focal plane

Control and Data Acquisition) tool, designed in a Labview environment in collaboration with the University of Almería, was installed during the first semester. This new application provides powerful graphical and control utilities and has been designed so that in successive versions, improvements such as shutter automation, of the greatest importance to system operation since it enormously facilitates testing and repeatability, can be incorporated.

This new control and acquisition system, which includes a Pentium 4 computer with two screens – a control screen and a graphical screen – shown in Figure 52, is an important improvement with regard to the previous acquisition system, as the most important data are shown in graphical form on one screen while the rest of the data are on the main screen.

Figure 52. New data acquisition system screens

In this context, several shutter automation tests have been performed with different control algorithms. The test pieces, copper wire matrices, were sintered in the Minivac. This type of test piece has been tested often, so the operating personnel know it well and this makes testing the various algorithms easier.

A new flux measurement system, including the Lambertian target from the old system has also been installed. It has a new Hamamatshu C4880-21CCD camera with two A/D converters providing two reading modes: a 12-bit converter for fast reading and a 16-bit converter for precision reading. Its typical real dynamic range with the 16-bit A/D converter is 37500:1.

The system software is Media Cybernetics Image Pro Plus, which is one of the best known and most popular among data acquisition and image analysis program users. It includes a wide range of possibilities for capture, from videos to digital photographs and CCD cameras and other scientific instruments, with high quality and accuracy. It also makes a wide variety of image processing tools available to the user.

SOLAR FUELS AND INDUSTRIAL PROCESSES

Emerging activities in the High-Temperature Solar Energy Project include production of different energy vectors of electricity that make possible seasonal storage, transport and integration in industrial processes of solar energy, and that require adaptation of the process to solarize their endothermal stages. Integration in industrial processes is basically dealt with under the nationally coordinated SOLARPRO project, which has already been presented in the section above. Research in the production of solar fuels revolves around solar hydrogen production as shown in Figure 53.

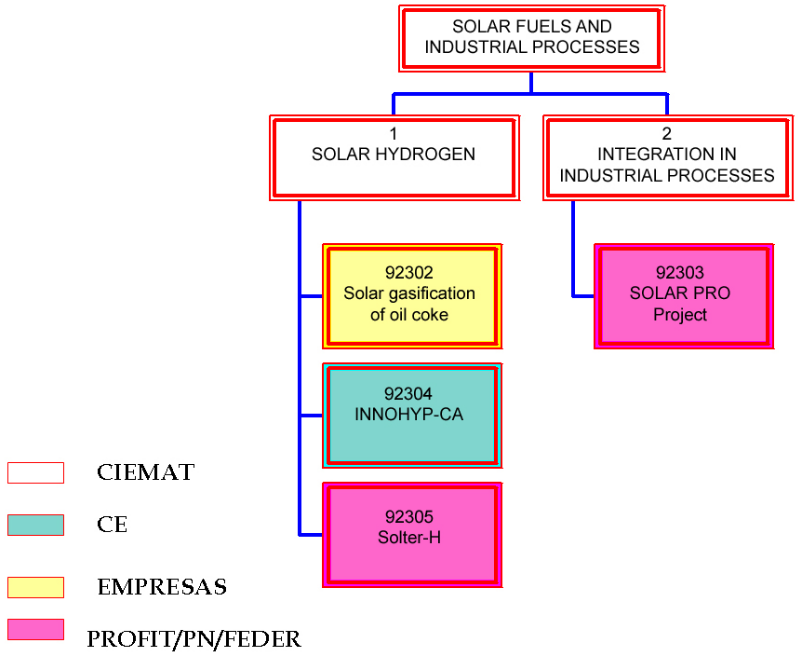


Figure 53. Structure and content of the lines of research in solar hydrogen and integration in industrial processes. Colors indicate sources of funding

Solar gasification of oil coke

The complete replacement of fossil fuels is a long-range goal that requires the development of new technologies. Strategically, it is desirable to consider intermediate mid-term objectives that develop hybrid solar/fossil endothermal processes, in which fossil fuels are used exclusively as chemical reagents and solar energy as the process heat source. An important example of the hybrid process, and certainly one that probably will cause the most impact, is solar gasification of oil coke. The results are cleaner fuels with an energy content whose calorific value is improved by solar energy over the primary raw material by an amount equal to the enthalpy exchange of the reaction. The mixture of oil coke and solar energy creates a link between today's oil technology and the solar chemistry of tomorrow.

Oil coke gasification is a complex process, but the overall chemical conversion can be represented by this simplified net reaction:

$$C_1H_xO_y + (1-y)H_2O = \left(\frac{x}{2} + 1 - y\right)H_2 + CO$$

Where x and y are the elemental molar relationships of H/C and O/C in oil coke, respectively. The chemical obtained is syngas, the quality of which depends on x and y.

The oil coke solar gasification project is being done in collaboration between Petróleos de Venezuela (PDVSA), the Technical Institute of Zurich (ETH) and the CIEMAT, and its main objective is to develop a clean solar gasification technology for oil coke and heavy oil in general. In the first phase, the project focused on characterizing the process for three oil cokes from heavy crude production in the Orinoco belt in Venezuela: Flexicoke, and Petrozuata and Amuay delayed cokes. The kinetic-chemical tests performed in kinetically controlled laboratory reactors have confirmed the high quality of syngas produced at temperatures over 1300K, where practically gas composition is reduced to CO and H_2. The gas obtained is highly clean, since there are no combustion gases, and all of the coke has been employed as a chemical reagent. The kinetic constants and corresponding kinetics model have been obtained, and a reactor matter and energy transfer model to analyze

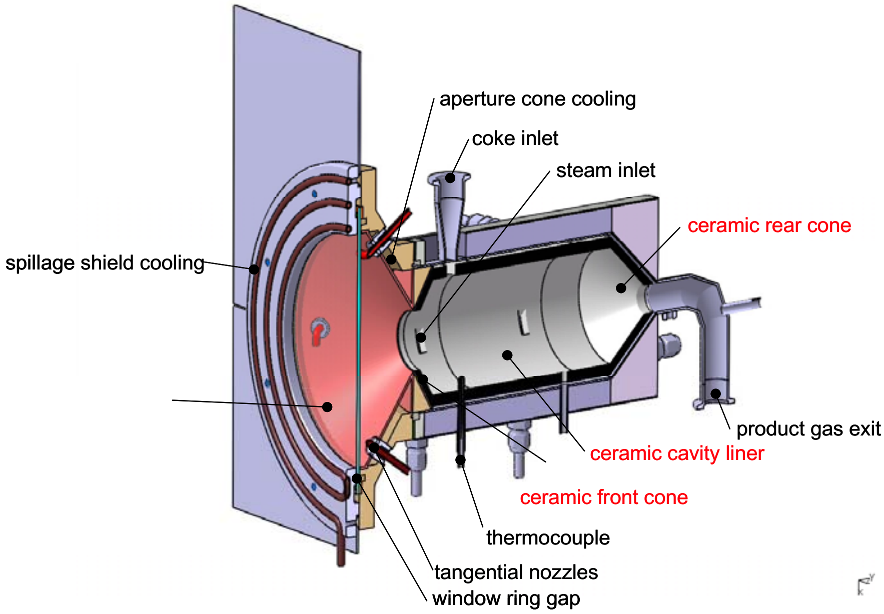


Figure 54. Diagram of the 5-kW solarized chemical reactor used for oil coke gasification (joint PDVSA, ETH, CIEMAT Project)

the fluid-dynamic behavior of 1-to-100-micron particles was developed using the Fluent® code.

An exergetic analysis has been made based on the second law of thermodynamics, to examine two technically viable pathways to obtain energy from gasification chemicals, and establish a basis for comparison with conventional power plants. The two pathways are: 1) the syngas is produced by solar gasification with oil coke vapor is used as fuel in a combined Brayton-Rankine cycle with a performance of 55%, and 2) the syngas produced by solar gasification with vapor is reprocessed to H_2 by a displacement reaction, followed by separation of H_2/CO_2, and the H_2 is then used to feed a fuel cell with 65% performance. The exergy analysis indicates that both pathways can double the specific electricity output (6.6 kWh/kg coke) and thereby reduce to half the specific emissions of CO_2, compared to the Rankine cycle fed by fuel with a performance of 35%.

Phase 1 of the Project, consisting of the design, construction and testing in the solar furnace of a 5-kW experimental reactor was completed in 2004. The reactor tested demonstrated the production of high-quality syngas from oil coke at an operating temperature of 1300-1800K, with conversions of 87% and residence times of 1 s. CIEMAT, apart from its participation in reactor testing in the PSI solar furnace in Switzerland, carried out a laboratory test campaign with a scale model heated by electrical heating elements in which new methods of feeding the coke in slurry were tested.

Phase 2, consisting of concept scale-up of the 500-kW pilot plant to be tested in the PSA CRS tower, will begin in 2005.

Hydrogen production by the thermochemical pathway (INNOHYP Project)

CO_2-emission-free thermochemical hydrogen production has recently been revitalized after two decades of ostracism and lack of interest. The solar high-concentrating technology has the capacity and properties required to be able to solarize large-scale hydrogen production processes, using high temperatures and thermochemical cycles.

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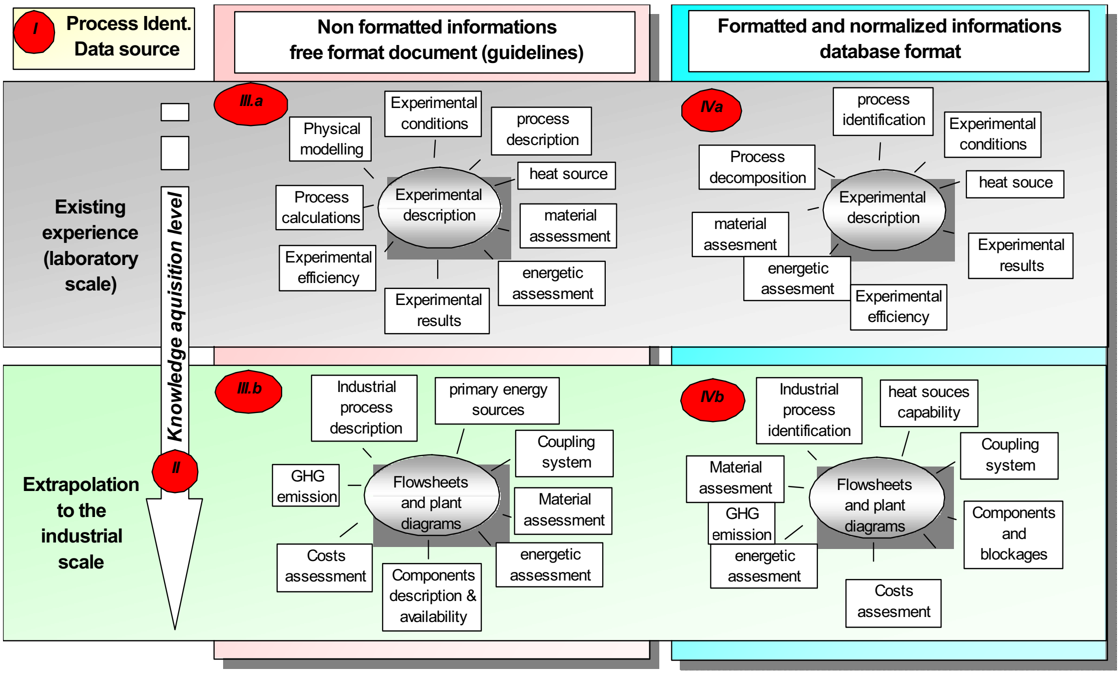


Figure 55. Methodology established in the INNOHYP Project for analysis of state-of-the-art thermochemical hydrogen mass production processes (Source: CEA).

The INNOHYP-CA project (Innovative high temperature routes for Hydrogen Production – Coordinated Action) is financed by the European Commission in its 6th Framework Programme, the purpose of which is to review innovative state-of-the-art CO_2-emission-free thermochemical hydrogen mass production processes. The project is coordinated by the French Commissariat for Atomic Energy (CEA) with the participation of seven other participants (ENEA in Italia, DLR in Germany, Sheffield University in the United Kingdom, Empresarios Agrupados and the CIEMAT in Spain, CSIRO in Australia and the EC Joint Research Centre in Petten, Netherlands). The study focuses on water dissociation by classical thermochemical cycles, such as UT-3 SI, Westhinghouse and metal oxide cycles like the ZnO cycle, mixed ferrites and others, like high-temperature electrolysis. Fossil-fuel decarbonization processes, like thermal cracking of methane, solar methane reforming and solar gasification of carbonic materials are also assessed. The INNOHYP project must further serve as a reflection of the technological challenges to be solved and propose areas of research and development, as well as acting as a bridge to other projects and road maps (Hyways Project), and for the mediation with international technological platforms and forums of collaboration such as the International Energy Agency and the IPHE (International Partnership on Hydrogen Economy)

The project began in September of 2004 and will last two years. In 2004, the kickoff meeting was organized by the CIEMAT in Madrid, where the basic principles for the analysis and comparison methodologies for the different processes were agreed upon. An overview of the state-of-the-art of the various processes is expected to become available in 2005 that will enable the comparison and corresponding road-mapping to begin in early 2006.

Hydrogen production from metal oxides (Solter-H Project)

Among the multitude of endothermal processes of interest for solarization, those based on the use of metal oxides are especially attractive. The Solter-H project is a project financed by the Ministry of Education and Science PROFIT program, in which Hynergreen and CIEMAT are collaborating. In this project, the state-of-the-art of several hydrogen production processes based on thermochemical cycles were reviewed for the purpose of selecting one to be developed later by the partners, first on laboratory scale and later scaling up to several kW in a solar furnace or dish.

Both the bibliography available and operating data existing for General Atomics and UT-3 cycles reflect excessive complexity, both with regard to the number of reactions involved and the development of adequate technology to solve some basic problems. This fact, along with some problems inherent in the operation of a solar thermal power plant, would complicate operation extraordinarily, since we would have to integrate the heliostat field control with several receivers, basic separation, purification and other operations. This interaction between the various field components would be even more critical in the presence of transients or even during periods of startup and shutdown . However, hybrid cycles, such as the Westinghouse cycle, although less efficient, with two clearly differentiated reactions, could present a viable alternative for a solar plant. As fruit of this reflection, we collaborated with the CEA and the DLR in the preparation of a proposal to the EC 6th Framework Programme, which unfortunately, was not given the funding requested. Nevertheless, this process has been retained as subject to be developed in future international collaboration.

In the national scope, collaboration between Hynergreen and CIEMAT in the development of a process to adapt the knowledge of both in solar concentrating technologies and volumetric solar absorbers has been considered more feasible. In this sense, mixed ferrites have some more attractive characteristics for their possible solarization. The absence of reliable data is, however, a strong limitation on beginning the solarization of this process. The Solter-H project is intended to develop the steps necessary for a techno-economic feasibility study to assess the use of mixed ferrites in solar reactors in laboratory tests and later in a small solar concentrate with several doped ferrites.

Mid-Temperature Solar Thermal Energy

Although the limits of the mid-temperature range are not defined by any standard, within the scientific community working in concentrated solar radiation, this range is usually considered to be between 150°C and 450°C. In any case, these limits must be taken with a certain amount of flexibility.

From a technological point of view, the use of solar energy in the mid-temperature range is associated with a specific type of solar collector, the parabolic-trough collector (PTC). Although recently, another type of solar collector is also receiving attention for solar applications in the mid-temperature range, the linear Fresnel collector (LFC), the degree of technological maturity and commercial development of the PTC is much greater. Therefore, the activities carried out at the PSA in the Mid-Temperature Solar Thermal Energy Program are closely related to PTC technology and applications.

Parabolic-trough collectors (PTC) are linear-focus concentrating solar devices that convert direct solar radiation into thermal energy and are ideal for working in the mid-temperature range. The concentrated direct solar radiation incident on the aperture plane of the collector efficiently raises the temperature of the working fluid to over 400°C. For this reason, PTCs are ideal for powering industrial thermal processes between 150 and 400°C. Given the large number of processes that meet this condition, the commercial interest in PTC is very strong, since their commercial implantation could help significantly to arrive at the much desired Sustainable Development, by reducing the CO_2 emissions and environmental pollution involved in the use of fossil fuels.

A PTC is basically a parabolic-trough-shaped mirror that reflects direct solar radiation, concentrating it on a receiver tube located in the focal line of the parabola. This concentrated radiation heats the fluid that circulates through the tube, thus transforming the solar radiation into thermal energy in the form of the sensible heat of the fluid [Zarza, 2001]. Figure 56 shows a PTC and how it works.

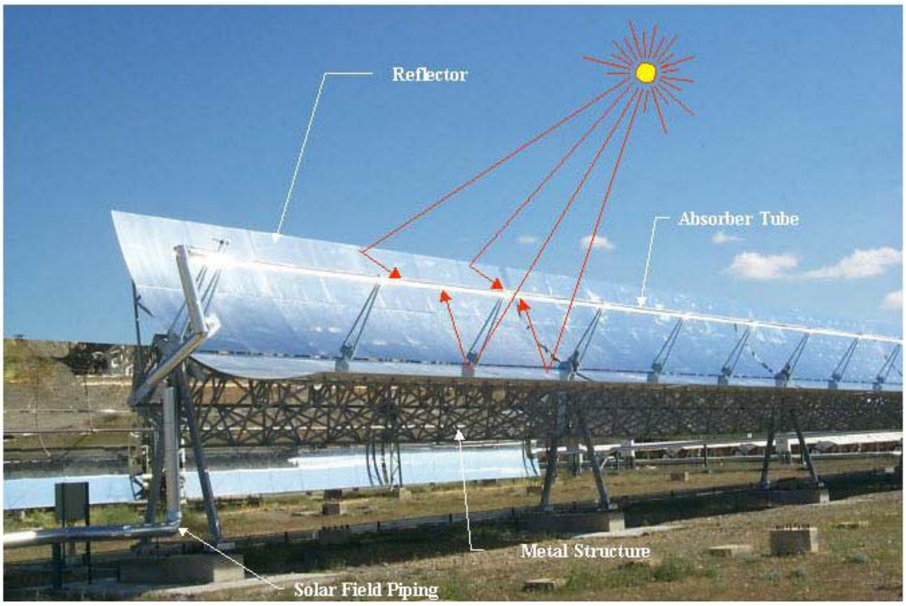


Figure 56. The parabolic-trough collector principle

The PSA Mid-Temperature Solar Thermal Energy Program promotes and contributes to the development of systems using solar radiation in the 150ºC-450ºC temperature range through several lines of PTC R&D, both for electricity generation and for industrial process heat. Its four main objectives are:

- Development of new PTC components (new absorber tubes, mirrors, lighter-weight structure designs, new solar tracking systems, etc.) with a better cost/quality ratio.
- Development of simulation and characterization tools of both collectors and complete systems
- Development of the *direct steam generation (DSG) technology* to eliminate the thermal oil which is currently used in PTC solar plants as a heat transfer medium between the solar collector field and the industrial process it feeds.
- Facilitate the development and consolidation of an indigenous national industry, through technical/scientific consulting and technology transfer.

The activities carried out at the PSA to accomplish these objectives are grouped in several different projects, each of which has its own group of partners, budget and planning. The final result pursued by this set of projects is increased competitiveness of parabolic-trough solar systems to promote the commercial implantation of this technology, in the case of electricity generation, a 26% reduction in the cost of electricity produced.

Within the 2004 PSA activities concerned with mid-temperature solar thermal energy, those related to direct generation of high-pressure steam have continued to occupy a central position, and among these, the PTC absorber tubes themselves. This new technology, known by the acronym DSG (Direct Steam Generation), continues to demonstrate that it is a an option of great interest for reducing the cost of thermal energy from this type of solar collector, since it allows the thermal oil and oil/water heat exchangers currently used in such facilities to be eliminated.

The technical and commercial maturity reached by PTC solar plants in the production of electricity (thanks to the valuable experience contributed by the California SEGS plants) contrasts with the lack of development in other likely mid-temperature solar applications, such as industrial heat processes and industrial heating and cooling of interiors. The lack of suitable solar collectors and industrial equipment for this type of application still requires intense R&D activity to reach the same level of development as electricity generation. Spain, like many other countries in the so-called Sun Belt, has certain climatic conditions that make these other parabolic-trough applications very attractive. Therefore, in 2004, PSA activity in this field has been widened to include development of industrial heating and cooling components and industrial heat processes. We are therefore participating in International Energy Agency Task 33/4 ('Solar Heat for Industrial Processes' or SHIP; www.iea-ship.org), so we can take advantage of the experiences and knowledge on solar thermal energy applied to industrial processes that other international entities possess. This has increased area of work related to the PTC, since it has traditionally focused on electricity generation (solar thermal power plants).

The activities performed by the PSA in 2004 under the Mid-Temperature Solar Thermal Energy R&D Program were mainly under four projects: *INDITEP*, *DISTOR*, *FASOL* and *PREDINCER*. Of these four projects, INDITEP has absorbed most of the resources and work, due to the significant participation of the PSA in that project. Below, the most relevant results obtained in 2004 by the PSA in these projects are briefly described.

INDITEP PROJECT

The 36-month INDITEP project officially began on July 1, 2002. It receives financial assistance from the European Commission (contract nº ENK5-CT-2001-00540) and the activities planned under the project constitute the logical technical continuation of DISS project activities (1996 – 2001). Once the technical feasibility of direct steam generation (DGS) had been demonstrated in the DISS project (Eck *et al*, 2003), the next logical step was process and essential component optimization and at the same time, the detailed design of a first commercial solar thermal power plant with DSG in the solar field could be undertaken.

The INDITEP project has four basic objectives:

1) Detailed design of a first commercial 5-MWe DSG plant
2) Optimization and development of advanced components to make the DSG technology more competitive (compact economical water/steam separators, thermal storage for DSG, etc.)
3) Characterization under real solar conditions of the most important DSG solar field components
4) Socioeconomic study of DSG technology

Most of the Partners in the INDITEP project (IBERDROLA, ABENGOA, CIEMAT, DLR, Flachglas Solar, GAMESA, INITEC, SIEMENS and ZSW) also participated in the DISS project, assuring perfect continuity of activities between the two projects. CIEMAT participation in INDITEP focused on the following activities in 2004:

- Participation in detailed engineering of a 5-MW_e DSG plant
- Improvement of the PSA DISS solar field to increase steam production to 1 kg/s.
- Operation and maintenance of the DISS plant with a view to operating and maintenance procedures for commercial DSG plants, and to evaluate new water/steam separators, thermal storage systems and reflectors.
- Analyze the stress in DISS collector absorber tubes after over 4000 hours of operation.
- Develop new selective coatings able to support temperatures of up to 550ºC.

The activities carried out at the PSA in each of these four areas are described below:

Detailed Engineering of a 5 MWe DSG plant:

The PSA simulated the annual behavior of a solar thermal power plant with direct steam generation for which the conceptual design had been completed in 2003 (González 2003). To do this, the solar field and the power block models designed by the PSA and IBERINCO, respectively, were implemented in TRNSYS and overall plant behavior was simulated based on the meteorological data corresponding to a PSA reference year. Figure 57 and the table below show main parameters of the power block and the solar field, which has a nominal electrical power of 5175 kW.

Main Parameters of the INDITEP Plant

Power Block	
Gross electrical power, kWe	5472
Net electrical power, kWe	5175
Gross performance, %	26.34
Net performance, %	24.9
DSG Solar Field	
Number of parallel collector rows	7
Number collectors per row	10
Length of each collector, m	98.5
Width of the collector parabola, m	5.76
Total aperture area, m2	38384
Peak thermal power (Ed=1kW/m2), MW	25

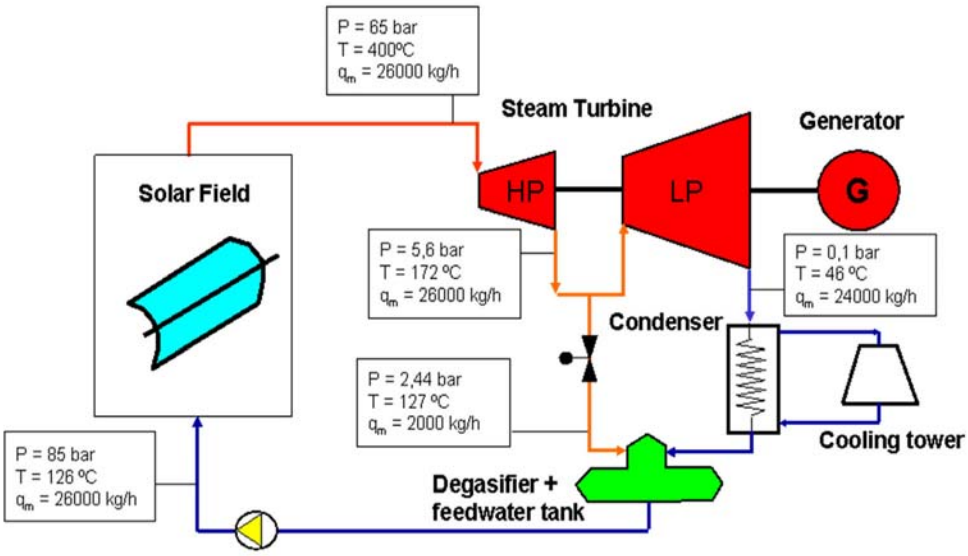


Figure 57. General flow diagram of the INDITEP solar thermal power plant

The net electrical power of the whole plant is 4839 kW, which is obtained by subtracting the parasitics in the solar field and auxiliary systems from the net electrical power of the power block. The following table summarizes the main results of the simulation of annual behavior of the INDITEP plant (Zarza, et al., 2004).

In 2004, the PSA also worked on development of INDITEP solar field system control (Valenzuela, Zarza 2004), and defining plant operating procedures in collaboration with DLR, IBERINCO and ZSW. A first draft of the start-up and shutdown procedures considered the best according to the experience acquired at the PSA with the DISS experimental plant in the last five years was completed. The control plant proposed in 2003 for the DSG solar field was also improved and completed.

Results of simulation of annual INDITEP plant behavior

Annual insolation from direct solar radiation, kWh/m^2	2008
Number of hours of sunlight per year	3685
Number of operating hours per year	2559
Net annual electricity, MWh	9431
Equivalent hours at full load	1949
Average performance of the solar field	61% (Summer) y 30% (Winter)
Average steam production in the solar field, kg/s	5,1 (70,6% of nominal value)

With regard to the detail engineering of the INDITEP plant in 2004, the PSA also collaborated with IBERINCO on the piping layout and design of main solar field elements.

DISS Plant Component Evaluation

Another important part of PSA participation in the INDITEP project in 2004 was devoted to testing the DISS experimental plant for assessment of new compact water/steam separators and continue testing different operation and control strategies. In 2004, the DISS plant was operated for a total of 1003 hours.

Figure 58. View of the compact water/steam separator tested in at the PSA in 2004

The main component evaluated in 2004 was a new prototype compact water/steam separator manufactured by the German Siemens Group company, Framatone. The figure below shows a view of this separator installed in the DISS plant, along with the old separator. The new separator is a piece of steel pipe 76.1 mm outer diameter and 1.5 m long. In the same picture you can see the traditional water/steam separator that was installed in 1998, which was 76.1 mm outer diameter by 2.5 m long. The difference in size between one separator and the other can clearly be seen. The cost of the new separator is only 10% of the cost of the traditional separator, which will significantly reduce the cost of the DSG solar field. The experimental results obtained with the new separator have been evaluated by DLR, which has verified the good behavior of this new prototype separator, as the separation efficiency is very high (>90%) and the pressure drop that it produces in the circuit is rather low (<1 bar) for a 1 kg/s flow rate.

Some other improvements have also been made in the DISS plant in 2004. An example of these improvements is the installation of manual insulation valves at the entrance to all the injector control valves, which permits the injection of small amounts of water even though the valves have been given the close command. With the installation of the new manual valves, absence of undesired water flow through the injectors can be ensured.

In 2004, in with the collaboration of the PSA Electronics Office, improvement of local open loop controls installed in the DISS plant collectors continued. Hardware and software improvements have increased efficiency and reliability of the control system developed by the PSA for parabolic-trough solar collectors. Accumulated PSA experience in open loop solar tracking by calculating the solar vector and measuring the position of the rotation axis of the collector has allowed a degree of reliability and precision that surpasses what is required for commercial installation. It has also been verified at the PSA that the development of reliable, accurate solar tracking systems is much more complex and delicate than what might seem at first sight, since many points have to be taken into account that are easily overlooked without good practical experience in these systems. This high level of accuracy and reliability has been achieved thanks to the improvements that have been implemented during the last five years and the thousands of hours of experience acquired in experimental evaluation of the successive prototypes at the PSA.

Keeping in mind current industrial and commercial interest in solar thermal power plants with parabolic-trough collectors in Spain, and since the local control system developed by the PSA has reached a high level of perfection, the next steps to be worked on at the PSA will be its integration in an overall plant architecture suitable for today's technology.

Among the DISS plant tests planned for 2004 are new rotating joints suitable for 100 bar 550ºC water/steam, supplied free of charge by the HYSPAN company. Testing at temperatures over 300ºC will be done at the ENDESA power plant in Carboneras, Almería ("Coast of Almería Power Plant"), while it was decided to carry out at the PSA tests up to 300ºC and pressures of up to 70ºbar. To do this, the test equipment developed by the PSA during the first phase of the DISS Project, was connected to the high-pressure steam circuit. This equipment allows rotating joints to be subjected to consecutive cycles of rotation and pivoting under real temperature and pressure conditions. The existence of charge cells, thermocouples and pressure transmitters allows the pressure and temperature in the rotating joint to be monitored, as well as the stress caused by internal friction in the rotating joints as they move. The figure below shows the rotating joint test equipment installed at the PSA DISS plant.

Figure 59. View of the rotating joint test device in the PSA DISS plant

DISS Collector Absorber Tube Corrosion Study

In collaboration with the CIEMAT Materials Group, a stress and corrosion study was carreid out on the PTC absorber tubes of the DISS experimental plant after 4000 hours of operation with direct steam generation (Diego, Gómez 2004). To perform this study, five samples were taken from the pipes: one sample was taken from feedwater tube at the solar field inlet, and two samples were taken from the third absorber tube in collector number 9, and another two were taken from the first absorber tube in collector number 10. All the samples were analyzed using optical and scanning electronic microscope energy dispersive X-ray spectroscopy (SEM/EDX).

The analysis of the samples revealed the presence of zinc from an unidentified source on the inside walls of all of the samples. Very slight corrosion was observed on the sample from the feedwater pipe, while the samples from the absorber tubes from the superheated steam zone a mixture of combined corrosion and erosion that showed a rather uniform appearance and that affected 0.4% of the thickness of the pipe, which means a thickness of 0.04 mm affected by corrosion (see Figure 60 below). In some occasional zones, deeper corrosion was observed in a very small area going down to 2.65% of the pipe thickness. (see Figure 60).

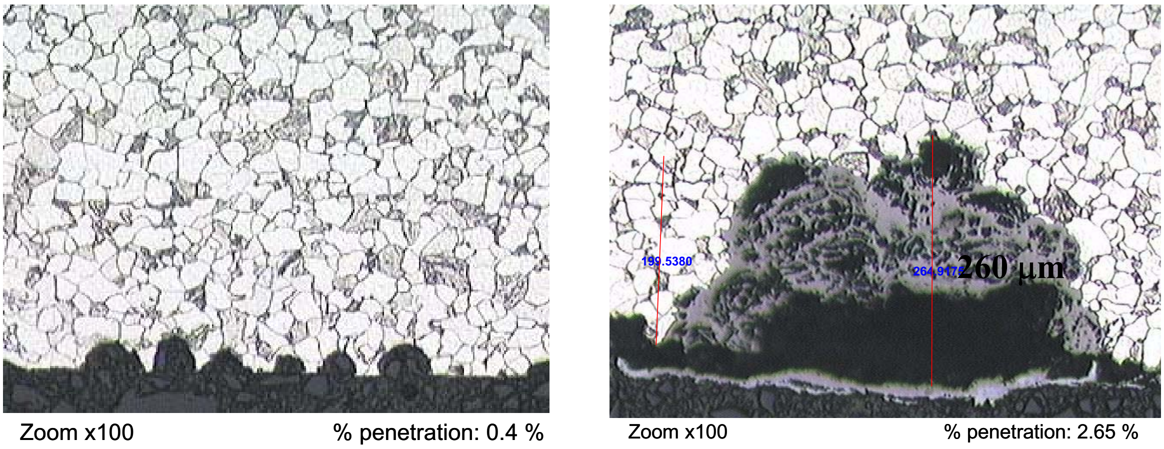


Figure 60. Condition of the DISS collector absorber tubes DISS after 4000 hours of operation.

Development of new coatings using the Sol-gel technique

In 2004, in the framework of the INDITEP project, the PSA continued to work on antireflective coatings for glass and selective absorber tube coatings. Activities in these two fields is summarized below.

a) Antireflective coatings on glass.

In 2004, progress continued on optimization of antireflective porous silica films on borosilicate glass, material used in the fabrication of the glass covering of parabolic trough collectors. The thickness and porosity of the silica film were optimized for maximum glass

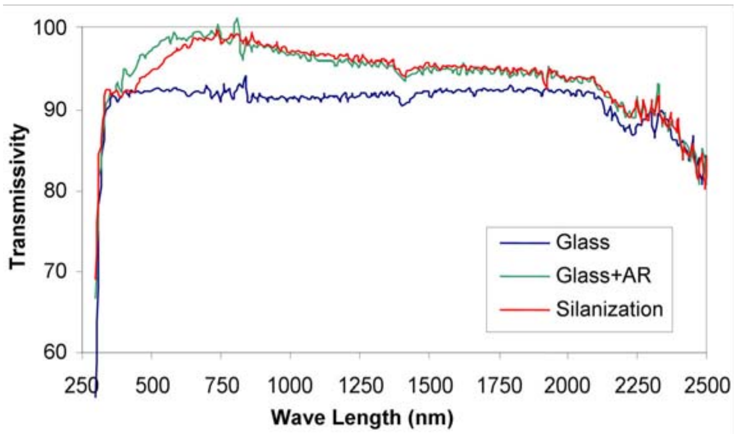


Figure 61. Solar transmittance of borosilicate glass without coating, with porous silica coating, and after silanization treatment

transmittance with a single antireflective coating.

The problem of steam adsorption by silanols (Si-OH) in the antireflective porous silica coating has been solved by inserting the sample in an alkyl alkoxide solution. This replaces the silanol radical –OH, avoiding water adsorption and conferring the coating with clear hydrophobic behaviour.

In the figure below the solar transmittance (AM1.5) of borosilicate glass used (0.923), of the glass with recently deposited antireflective coating (0.968) and after silanization treatment to avoid water adsorption (0.962).

Preliminary results of accelerated aging in a QUV weather chamber with condensation, temperature and UV radiation cycles indicate that the film is not degraded after 1000 hours of testing.

b) Selective absorbent coatings stable at high temperatures.

The INDITEP project means an increase in operating temperature of the selective absorptive coating of from 400ºC to up to 50-550ºC which, along with the use of carbon steel for the absorber tube, have made it necessary to make significant changes in the selective absorptive coating developed previously for deposition on the stainless steel tubes.

The new absorptive coating consists of two layers of alumina/platinum cermit with different metal content on a platinum reflector. Different protective barriers and/or antidiffusers are used between the layers, as well as an antireflective coating.

Direct Steam Generation makes it desirable to use carbon steel as the absorber tube material. Carbon steel has low chemical and thermal stability impeding direct deposition of sol-gel on the substrate. Therefore, the use of an intermediate film is necessary to confer steel with the thermal stability required to be able to densify the sol-gel films at temperatures of 550ºC. Therefore, nickel-tungsten films were deposited by electrolysis t allow densification of successive layers of absorptive cermet at temperatures of 550ºC.

The optical properties of the selective absorptive coatings on carbon steel are (as shown in Figure 62) are: α=0.95 y ε_{400C}=0.14.

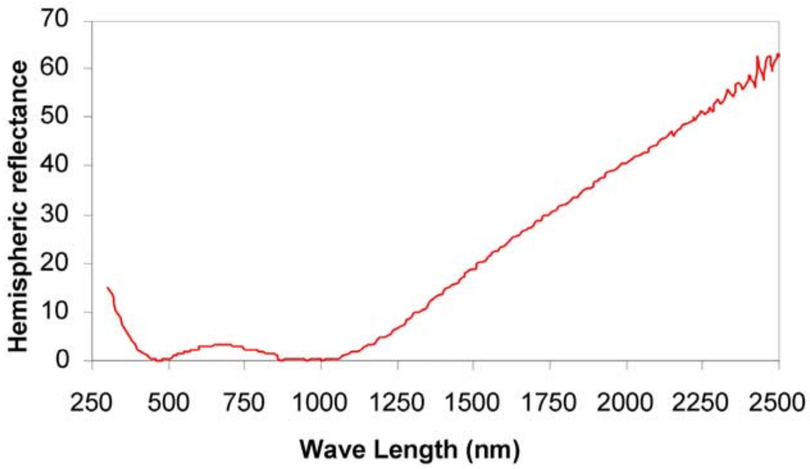


Figure 62. Selective absorptive coating deposited by sol-gel on carbon steel.

The selective absorptive coating for the thermal stability study was prepared with single films sintered in air at 600ºC for thirty minutes to achieve greater densification. When thermal stability in air at 550ºC was assessed, progressive degradation of the optical properties was found due to slow oxidation of the nickel-tungsten film used to protect the carbon steel substrate. A way to increase the tungsten content in the film to augment its thermal stability is currently under study.

DISTOR PROJECT

The DISTOR project is a European R&D project receiving support from the European Commission (contract no. SES6-CT-2004-503526). It officially began in February of 2004 and lasts 45 months. The main purpose of the DISTOR project is to develop a competitive storage system suitable for solar plants with direct steam generation in the solar field. They storage systems currently available for solar plants that use oil as the working fluid in the solar field are based on storage of thermal energy in the form of sensible heat (increasing the temperature in the storage medium). Since steam releases thermal energy when it condenses and this takes place at constant temperature, traditional thermal storage systems do not work with direct steam generation solar plants. So the purpose of the DISTOR project is development of a thermal storage system based on latent heat with phase-change materials.

The economic target of the DISTOR project is a specific cost of 20€/kWh rated capacity of the storage system, since at this cost, its implementation in commercial solar thermal power plants would still be profitable.

The many participants in the DISTOR project are coordinated by the DLR: CIEMAT-PSA, Sistemas de Calor (Spain), INASMET (Spain), IBERINCO (Spain), DEFY Systemes (France), EPSILON Ingénierie (France), SGL Technologies GMBH (Germany), FLAGSOL GMBH (Germany), Sanlucar Solar Solucar, S.A. (Spain), ZSW (Germany), Weizmann Institute of Science (Israel), y el Central Laboratory of Solar Energy and New Energy Sources (Bulgaria).

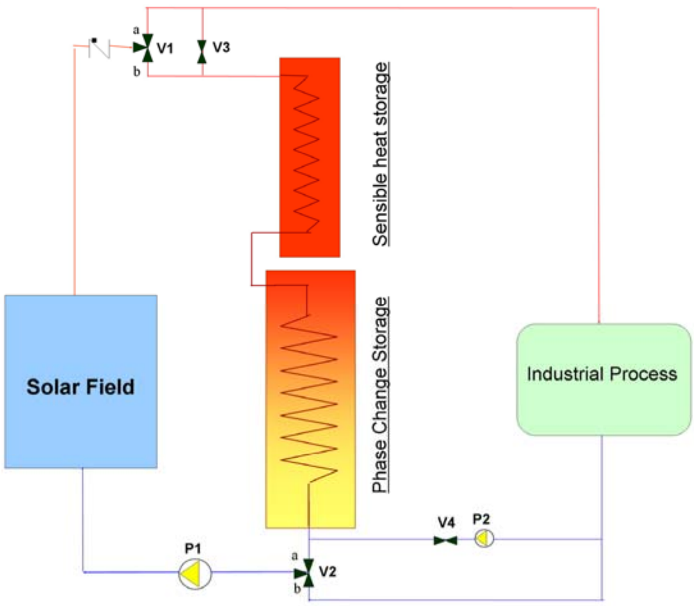


Figure 63. Diagram of thermal storage in a solar plant with direct superheated steam generation

In the DISTOR project, different thermal storage system configurations based on salts with a melting point in the range of 250ºC-290ºC apt for absorbing the latent heat released by the steam as it condenses at pressures between 70 and 100 bar. The phase-change storage system being developed under the DISTOR project has to be supplemented by a sensible heat storage system if it is going to work with superheated steam. Since comparative studies carried out on the two current options for direct steam generation plants show that, from the point of view of the steam (saturated or superheated), both options have advantages and disadvantages compared to the other, neither of them can be discarded, as there is not sufficient experimental data to back up a decision of this type (Eck, Zarza, 2004).

In 2004, the PSA performed a study on the various possible configurations for connecting a phase-change thermal storage system to a direct superheated steam generation solar plant. As may be observed, the storage system is composed of two different blocks connected in series: one based on latent heat (change phase) and the other sensible heat. During the discharge of the storage system, the part corresponding to latent heat is the one in charge of producing saturated steam, while superheated steam is produced by the sensible heat storage system.

The study performed by the PSA (Zarza 2004) has demonstrated the advantages of having a storage system divided into modules. As shown in Figure 64, a modular design of the storage system has the advantage of greater operating flexibility and greater reliability since a system failure would only leave the module affected out of service. Another additional advantage of the modular design is that the direct solar radiation is made better use of on days with slight but frequent transients caused by isolated clouds. In this case, the storage system can be used to buffer the transients caused in the steam parameters at the solar field outlet. To do this, all the thermal energy supplied by the solar field is sent to the storage system, which is then in charge of producing the industrial process steam demand. The production of steam in the storage system would begin once the first module of the system is 100% charged, so that the solar field would then start to charge the second module while the energy stored in the first module is used to produce the steam required by the process.

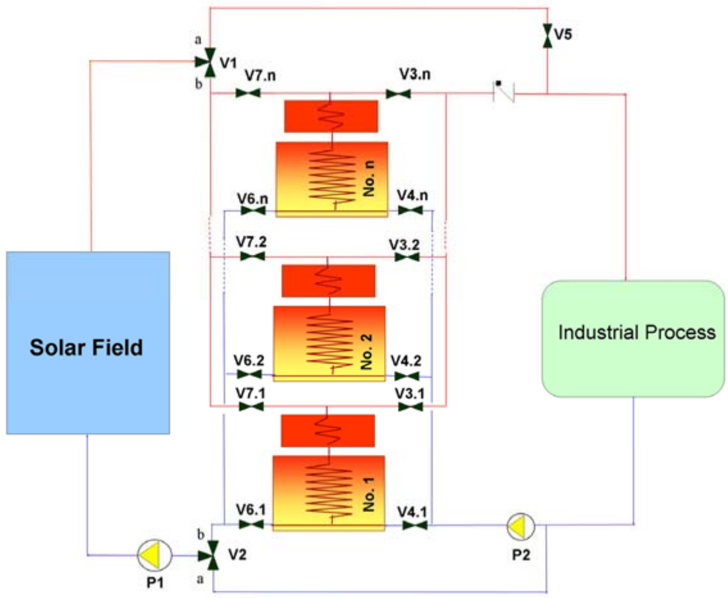


Figure 64. Simplified diagram of a modular storage system for a direct superheated steam generation plant (each module is composed of two sections connected in series: one with phase change and the other storing sensible heat).

FASOL PROJECT

The purpose of the FASOL project is to develop a new medium-sized parabolic-trough collector suitable for small and medium applications of solar thermal energy up to temperatures of 300°C. There is a current shortage of offer in this field, so it is of interest to develop a PTC with a good quality/cost ratio and a size adequate for feeding industrial thermal processes with a moderate power demand. There are many industrial processes that consume thermal energy within the mid-temperature range, but for them the parabolic-trough collectors developed to date, intended for large solar thermal power plants (LS3 and EuroTrough collectors) and over 500,000 m² solar fields, are excessively large. Obviously, for small applications, a PTC should not the same size as for large fields. Therefore, the PSA, in collaboration with Castaño Bolea e Hijos S.R.L. and the consulting by independent experts (José Fuentes and Simón Avila), has undertaken the design of a medium-size PTC that would be suitable for small or medium applications. This project, called

FASOL, receives financial assistance from the National Energy Program, under the National Scientific Research, Development and Technological Innovation Plan (PROFIT).

The FASOL prototype parabolic trough was developed and fabricated with the following main characteristics:

- Parabola width: 2.6 m
- Concentrator module length: 6 m
- Total collector length: 50 m
- Structure: Molded composite reinforced with parabolic metal ribs
- Reflector: conventional silver-coated (1.2 mm thick) thin-glass mirror

In 2004, two 3-m-long parabolic-trough prototypes (see Figure 65) were fabricated and evaluated). After fractures appeared in the thin-glass mirrors, they were evaluated and different alternatives were studied, among which are first-surface silver mirrors on sheet metal suitably protected for outdoor exposure. This protection is the most critical point, so several different options were evaluated and durability testing with accelerated aging in weather chambers was begun. Accelerated-aging tests showed that none of the coatings tested sufficiently protected the silver film on the first-surface mirrors, so this line of research is still ongoing.

Figure 65. View of one of the parabolic-trough concentrator prototypes fabricated in the FASOL project

Among the conclusions arrived at from the work carried out in 2004 are:

- Because composites treatment and handling requires specialized personnel, for structural development with composites, collaboration with a company specialized in the sector is indispensable (none participated in this project), as in solar collectors, defects in shape, which in other applications may not be so important, are critical to their optical quality and thereby, their overall performance.
- Thin-glass reflectors currently on the market are too fragile to be easily fit to a parabolic structure with a small curve radius, because they are not factory tempered. The development of new parabolic-trough collectors would be considerably favored if there were outdoor reflectors that were sufficiently flexible for small curves.

PREDINCER PROJECT

The PREDINCER project is a coordinated national R&D project (CICYT) partly funded by the Ministry of Education and Science. It began in 2002 and is due to finish in November of 2005. In the framework of this project, the PSA collaborates with research groups from the Universities of Almería and Seville in the development and evaluation of new predictive control algorithms for processes with bounded uncertainties applicable to parabolic-trough collector fields.

Activities concern three main points: a) design of dynamic models and bounded uncertainties for certain processes, b) based on these models, resulting controller implementation and computation requirements, and c) guaranteed controller robustness. The activities performed by the PSA are related to the study of DISS plant direct steam generation behaviour (Valenzuela et al, 2004). The solar field operating configuration is flexible (Recirculation and Once-through modes) but, regardless of the configuration selected, there must be either a multi-loop control structure (SISO control) or a multi-variable control structure (MIMO control). The PREDINCER project has selected the SISO control structure and is designing predictive controllers for it.

The main results obtained are: a) acquisition of new knowledge derived from the application of modeling techniques (identification of parameters and application of first principles (non-linear modeling)) that make it possible for us identify the boundaries of uncertainties in the parameters or errors in processes similar to those studied and b) implementation and use of techniques that enable compatibility of computer tools other than modeling and control. Modeling was done with the Dymola/Modelica tool, which enables dynamic system behavior applying modeling techniques based on first fundamentals (mass, energy, momentum), but from experimental data and by parametric identification, we have also obtained low-order dynamic models with additive uncertainty of the type:

$$\sum_{i=0}^{n_a} a_i y(t) = \sum_{i=0}^{n_b} b_j u(t-d-j) + e(t)$$

These models are being used for the application of robust model predictive control techniques (robust MPC). To design the MPC controller, taking into account the uncertainties or discrepancies between the model and the plant, the worst possible case of output calculated by the model can be considered. Then an algorithm is implemented to minimize the maximum classical MPC target function for all the uncertainty values considered (min-max predictive control), that is, the optimum sequence of controller actions calculated as:

$$u^* = \arg \min_{u \in U} \max_{\theta \in \Theta} J(u,\theta)$$

where U is the set of sequences of admissible actions, θ represents the uncertainty and Θ is the set of values of the uncertainty considered.

In 2004, an OPC data server was also implemented (OLE for Process Control) in the PSA DISS plant control and data acquisition system (SCADA). The OPC enables the DISS plant SCADA (ABB Infi90) to communicate with the modeling and simulation tools (Modelica/Dymola or Matlab/Simulink) in real time for controller development and implementation.

OTHER ACTIVITIES IN 2004

Among the additional activities carried out by the PSA within the framework of the INDITEP, FASOL, DISTOR and PREDINCER projects was participation in the International Energy Agency's Task 33/4 8'Solar Hat for Industrial Processes', SHIP; www.iea-ship.org), to be able to make use of the experience and knowledge on solar thermal energy applied to industrial processes that other international entities have acquired. Our participation in Task 33/4 is mainly in Subtasks C (Collectors and Components) and D (System Integration and Demonstration), sharing experiences with the rest of the participants in the field of solar energy applications to industrial heat processes that operate in the 100ºC-250ºC temperature range. At the end of 2004, we began to prepare the Workshop to be held in Madrid at the end of February 2005 coinciding with the GENERA '05 Energy Fair.

The new legal framework defined in Spain for solar thermal power plants based on the conditions in Royal Decrees 436/2004 (BOE of 27/03/2004) and 2351/2004 (BOE of 24/12/2004), has given an important boost to Spanish industrial activity related to this subject. The premium of 0.18€/kWh established for electricity produced by concentrating solar power plants in any of its three variants (parabolic-trough, central receiver or disk/Stirling), along with the possibility of 12% to 15% hybrid gas per year, has attracted the interest of investors and industry to solar concentrating technologies. These attractive conditions have motivated many companies to come to the PSA for consultancy and collaboration, and a considerable effort has been made to provide assistance and consulting on parabolic trough collectors. Along this line, the PSA organized an intensive course on this subject during the first week of November 2004, which was widely attended by students from diverse sectors involved in the Spanish energy market.

Environmental Applications of Solar Energy and Solar Radiation Characterization

INTRODUCTION

In 2004, the "*Program*" previously called "Chemical Applications of Solar Radiation" was renamed "Environmental Applications of Solar Energy and Characterization of Solar Radiation". This name change does not mean any significant change in activities carried out, but reinforces and widens them, in order to strengthen them and make them compatible in every way possible.

Perhaps the clearest cases is processes associated with the use of solar radiation to include different water problems. In this field, the broad experience accumulated in the field of solar photocatalysis for water detoxification has been very useful to promote other initiatives, such as disinfection of drinking water and solar desalination of sea water, which has enabled a remarkable complementarity in both scientific and technological developments in the framework of several different projects. This subject of water is intended to be one of the main areas of research in this program because of its importance and social impact. In this sense, all international organisms clearly recognize that the shortage or lack of water is going to be one of the major challenges to face humanity in the first half of the 21st Century. All of this makes the challenges, opportunities and possibilities for the development of environmentally-friendly water technologies offering effective solutions for the imminent future that much more important.

Another important field of activity is and will continue to be, the photocatalytic treatment of gas, a process for which some equipment is already available commercially, although using light generated by electric lamps. In 2004, certain Spanish companies have shown a growing interest in the possibilities for elimination of odors and gas pollution in general offered by solar technology.

The most outstanding innovation in the CIEMAT reorganization implemented this year has been the incorporation of the group devoted to measurement and characterization of solar radiation from satellite imaging (previously under the "Evaluation of Renewable Energy Resources" program). The possibilities and potential this incorporates for the whole group are very important given, on one hand, the relevance that the characterization of solar resources has in and of itself and, on the other, the strong interest that analysis and modeling of solar radiation available at specific spectral intervals, such as the ultraviolet radiation in photocatalytic processes. However, clearly, the field of greatest activity of this group is focused on the characterization and determination of the solar radiation available for the potential installation of solar power plants, a field currently experiencing a boom and under rapid development, and in continuous demand by interested businesses.

Many outstanding milestones were achieved in 2004. However, if any of them are to be given special mention, two would have to be cited for their special relevance. The first is the inauguration of the first commercial solar detoxification plant for the treatment of rinse water from a pesticide container recycling plant. This project, promoted by the Albaida Recursos Naturales y Medioambiente company, is based on scientific and technological developments at the Plataforma Solar de Almería in recent years. The second milestone was the award of the 2004 European Gran Prix for Innovation in the category "Jury's Award" to two of the group's members (Drs. Julián Blanco Gálvez and Sixto Malato Rodríguez). This award means, apart from the obvious satisfaction of the scientists involved, important international recognition of the work that the group as a whole has been doing over the last few years.

The following sections briefly describe the main projects and activities performed in 2004.

1) Solar detoxification of liquid effluents
2) Solar disinfection of drinking water
3) Solar seawater desalination
4) Characterization and measurement of solar radiation
5) Solar energy storage

1) SOLAR DETOXIFICATION OF LIQUID EFFLUENTS COMBINED PHOTOCATALYSIS-OZONIZATION (PHOTOZONE) TREATMENT

ENVIRONMENTAL COLLECTION AND RECYCLING OF PLASTIC PESTICIDE CONTAINERS WITH SOLAR PHOTOCATALYSIS

This project studies the elimination of recalcitrant aqueous pollution using Advanced Oxidation Processes (AOPs). This innovative project arises from investigation of combined Photocatalysis-Ozonization, where considerable synergy has been observed in preliminary experiments, significantly increasing the detoxification capacity of both methodologies when used separately [Farré et al., 2004].

The general project objectives are the following:

1) Research in photocatalysis (homogeneous and heterogeneous) + ozonization synergies to find the optimum operating parameters.
2) Find the conditions leading to detoxification. Combine the proposed technology with a biological treatment. Application to detoxification of waste water.
3) Preparation of TiO_2 photocatalysts with improved response to sunlight.
4) Pilot-plant testing under sunlight. Real-scale validation of laboratory experiments. Application to solar purification of industrial waste effluents.
5) Design or pre-design of an effluent treatment plant.

The Plataforma Solar de Almería mostly participates in the second and third years of the 3-year project (2003-2205). In fact, in 2004, experiments were performed with the pilot plant installed for this purpose shown in Figure 66. The complete system consists of an ozone generator, pressurized oxygen bottle, ozonization column, recirculation pump, water rotameter and waste ozone destructor (to avoid emission of ozone into the atmosphere). The piping and valves through which

Figure 66. View of the ozonization system installed at the PSA.1, Ozone generator. 2, Contact column. 3, recirculation pump. 4, Ozone Analyzer. 5, Ozone destroyer.

the water circulates (with or without dissolved ozone) are made of polypropylene and piping through which O_2 and O_3 circulate are made of PTFE. The contact column is PVC, opaque at the base (and wider diameter, 200°mm OD) and transparent at the top (16 mm OD). This is because transparent 200-mm-OD PVC is not available on the market. The total system volume is 50.7 L, but depending on the amount of liquid in the system, may work at as little as 35 L, or a maximum of 46 L.

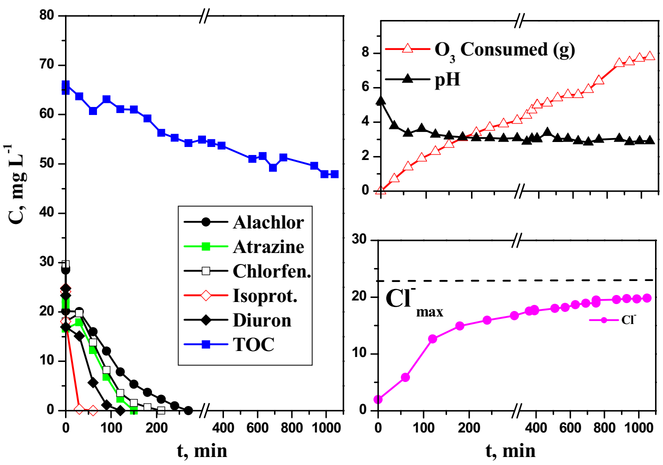


Figure 67. Degradation of various pesticides by ozonization (left). Production of chloride, ozone consumption and variation in pH during ozonization (right)

The suitability of this treatment (see Figure 67) with the compounds Alachlor, Atrazine, Chlorfenvinfos, Diuron and Isoproturon, all of which are considered priority hazardous substances by the EU (European Parliament and Council Decision No 2455/2001/EC of 20 November 2001 establishing the List of Priority Substances in the Field of Water Policy and Amending Directive 2000/60/EC. Official Journal of the European Communities, 15.12.2001). At the beginning of ozonization (first 30 minutes) the water becomes an intense yellow (because of pesticide degradation intermediates) which gradually disappears as the treatment continues. The pH also drops to about 3 (as inorganic acids are generated from the heteroatoms contained in the pesticide molecules) and the compounds are completely degraded (as demonstrated by liquid chromatography measurements). It should be remarked that although the compounds are substantially degraded (in fact, dechlorination is complete), Total Organic Carbon (TOC) measurements are reduced only 20%. Therefore, ozone is basically responsible for partial oxidation of the compounds contained in the test water, but not its complete oxidation to carbon dioxide. The most important conclusion of this preliminary study is that ozone alone is incapable of degrading the compounds, although it can transform them into more oxidized intermediates. Therefore, its application in photo-Fenton as a supplementary solar plant treatment is totally justified, more so, if possible, when ozonization is achieved at a pH near 3, which is the optimum pH for working with the photo-Fenton process [Agüera et al., 2004; Gumy et al., 2004; Gernjak et al., 2004a, 2004b, 2004c; Pérez-Estrada et al., 2004; Sarriá et al., 2004a].

ELIMINATION OF PERSISTENT POLLUTANTS BY ADVANCED OXIDATION (FOTODETOX). http://www.psa.es/webesp/projects/fotodetox/index.html

This project, financed by the Spanish National RD&D Plan began in 2004 and is coordinated by the PSA Environmental Applications of Solar Energy and Characterization of Solar Radiation Group. It also collaborates with the Chemical Engineering Department of the University of Almería and with the Textile and Paper Engineering Department of the Polytechnic University of Valencia. The basic objectives are the following:

1) Treatment of water containing pesticides with solar photocatalytic processes (photo-Fenton and TiO_2) in a pilot plant. Achieve optimum operating parameters.
2) Biodegradability studies using mono-specific bacteria cultures (selected from among those common in WTPs) in water polluted by pesticides and partially treated by photocatalysis. The bacteria strains will be assessed for pollutant biodegradation activity.
3) Development of predictive models for biodegradability of water partially treated with photocatalysis.

4) Biodegradability studies (using real activated sludge from WTPs) of water polluted by pesticides and partially treated by photocatalysis.
5) Development of a bioreactor specially adapted to this type of partial photocatalytic water treatment.
6) Predesign of a solar photocatalytic water treatment plant for pretreatment of water containing recalcitrant pollutants and making them compatible with the input requirements of an urban WTP.
7) During this first year, the pesticides used in intensive agriculture in the province of Almería have been studied exhaustively, and the use that is made of them in agriculture, water from rinsing treatment equipment, effluents from the agricultural produce industry, uncontrolled dumping of containers, etc. Figure 68 shows the structures that were finally selected. Moreover, the analytical techniques necessary for evaluating their degradation have been perfected and their non-biodegradability was demonstrated. One of the first tasks was the study of the feasibility of photocatalysis with TiO_2 of each pesticide in the solar pilot plant, some of which are shown in Figure 68.

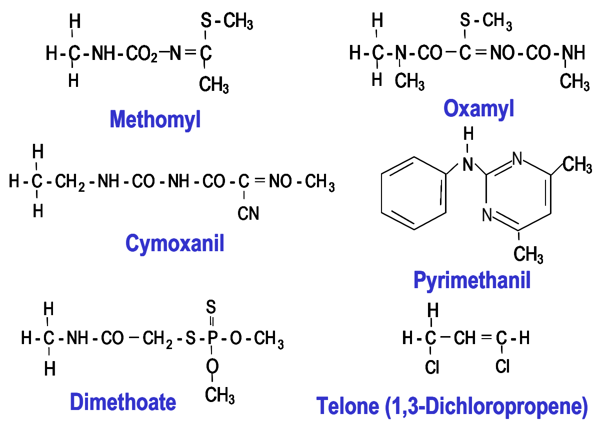


Figure 68. Pesticides selected for their widespread use in greenhouses and for their non-biodegradability.

The four pesticides shown in the figure are all completely degradable using TiO_2 with substantial mineralization better than 80% in all cases. Initial concentration was always the same (50 mg/L) and no adsorption was found on the catalyst surface. Figure 69 shows how after 15 minutes (t< 0) in the dark there was no variation in the concentration, which is

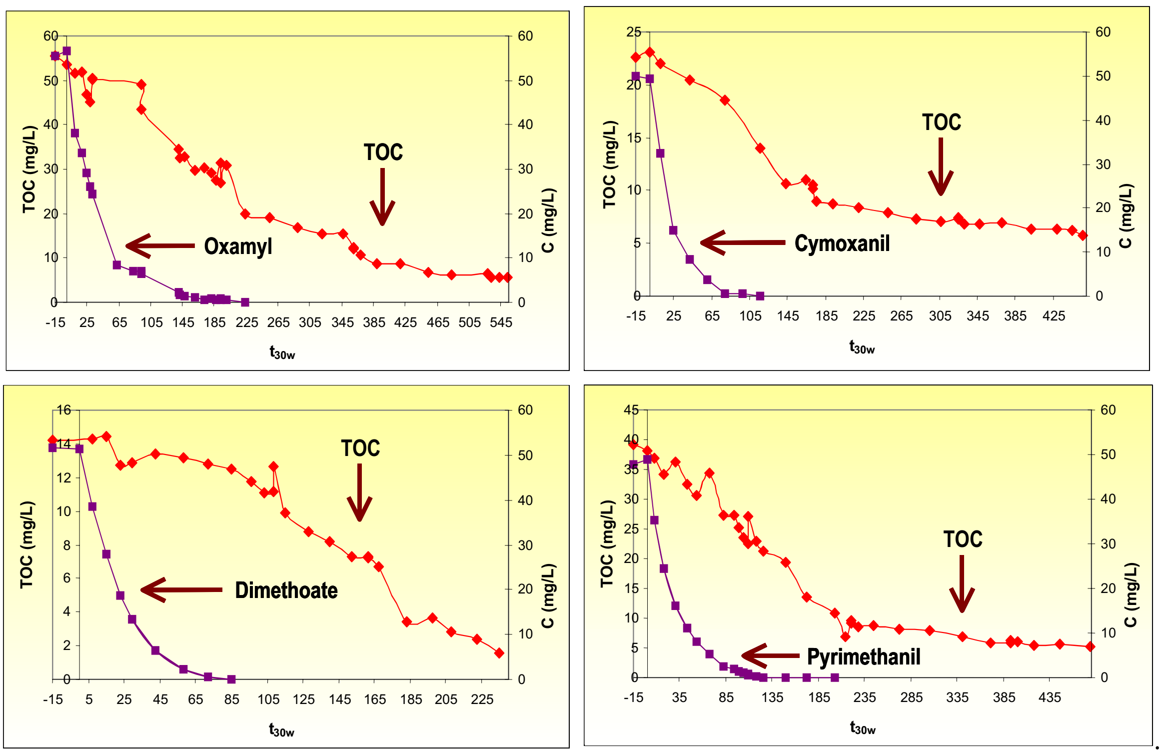


Figure 69. Photocatalytic degradation of 4 selected pesticides with TiO_2

diminished only when illumination begins (t=0). The degradation reaction kinetics were always the same, an apparent order of 1. That is, the rate diminishes as pollutant concentration decreases. Mineralization, however, does not follow definite kinetics since decomposition of TOC is governed by the decomposition of a very wide variety of compounds that are formed from the original pesticide due to the many oxidation steps (and even reduction) that lead to total oxidation (disappearance of TOC and formation of CO_2) only in the last step. The pesticide decomposed the fastest is cymoxanyl and the slowest is oxamyl, however, the behavior of TOC is also different, since it is precisely cymoxanyl which is least mineralized. Furthermore, the evolution of nitrogen was also monitored (that is, the conversion of organic N into nitrate and/or ammonia) and in no case could the balance of matter be closed. The most immediate conclusion is that there is an important part of N still contained in the remaining TOC or that it has been released into the atmosphere in the form of N_2.

TREATMENT OF WATER CONTAINING RECALCITRANT ORGANIC POLLUTANTS BY A COMBINATION OF ADVANCED OXIDATION AND BIOLOGICAL PROCESSES (CADOX).

http://www.psa.es/webeng/projects/cadox/index.html

According to the project objectives, defined in the annual report of the PSA for 2003, the primary tasks of the project have been designed to determine the main parameters for the degradation of the target compounds by each oxidation method (TiO_2, photo-Fenton and ozone) used in the project [Maldonado et al., 2004a]. It has been demonstrated that all the target compounds in this work can be successfully treated by photo-Fenton, TiO_2 and ozone [Malato, et al., 2004n]. The initial compound is quickly degraded and mineralization of TOC is slower with the photochemical methods (especially TiO_2), but by ozonization, mineralization is very low. The treatment time (for 90% mineralization) using 2 mg/L of Fe was no longer than 3 hours for the compounds tested. When a concentration of 1 mM Fe was used, the mineralization was achieved in less than an hour. This indicates that 2 mg/L Fe may be a good choice to guarantee sufficient degradation by photo-Fenton. 1 mM Fe might be necessary for treatment of waste water with hundreds of mg/L of TOC [Malato et al., 2004i, 2004l, 2004m; Maldonado et al., 2004b, 2004c]. In 2004, two prototypes were erected (one at the PSA and another at the INETI, Portugal) under the project with the main characteristics as shown in Figure 70

The main purpose of erecting these prototypes is to show that it is possible to treat water photocatalytically up to a level of degradation of pollutant content at which biological treatment is possible. Moreover, the possibility has been proposed that ozonization is

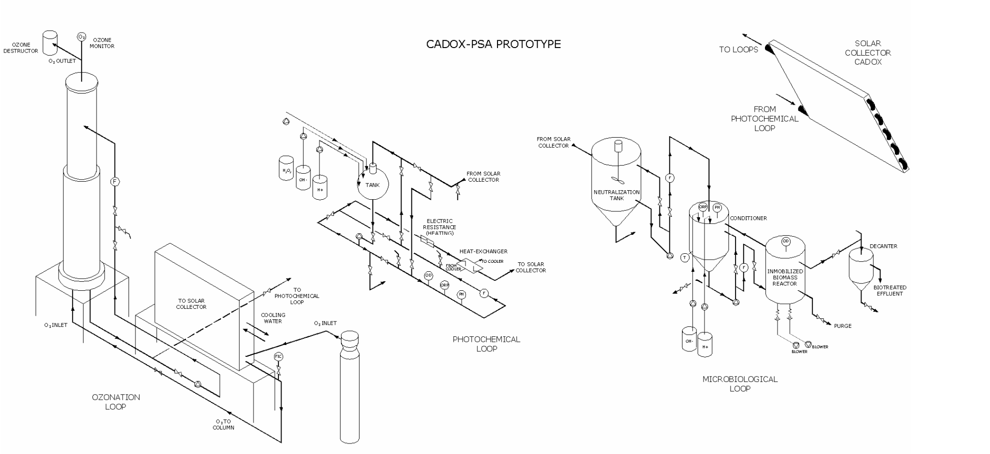


Figure 70. Drawing of the prototype erected at the PSA under the CADOX project, consisting of an ozonizer, a thermostatized photocatalytic reactor and a biological reactor with biomass in a fixed bed.

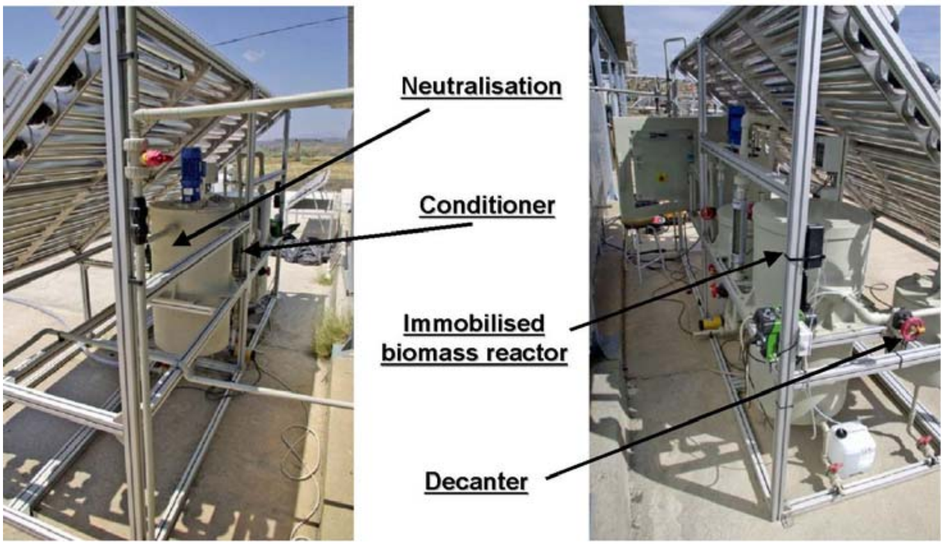


Figure 71. Biological reactor installed under the new CPC and connected to it at the PSA.

beneficial as pretreatment for photo-Fenton or even the combination of iron and ozone as an alternative to iron and hydrogen peroxide (photo-Fenton). A photoreactor better adapted to the photo-Fenton process than those existing before the project has also been designed and erected Figure 72, basically by increasing the diameter of the absorber and, thereby, the aperture of the CPC [Malato et al., 2004k]. Its main characteristic, in addition to the new CPC, is the possibility of temperature-controlled experiments. This was done so that the influence this parameter has on the photo-Fenton process could be properly evaluated. It is also equipped with the necessary instrumentation for proper control of pH and of hydrogen peroxide, parameters which must be controlled as well as possible in photo-Fenton. All of this will make it possible for testing to be done under the best conditions possible. Installation of the biological reactor will enable realistic experiments to be performed and demonstrate that it is the ideal photocatalytic pre-treatment for a biological reactor discharging water. The reactor (Figure 71) consists of a neutralization tank where the water is received from photocatalytic treatment for adjustment to the proper pH. From this tank, the water, which is in continuous recirculation with the reactor containing the immobilized biomass, is transferred to a conditioning tank (where all of the reagents necessary for the treatment are added). The immobilized biomass (on an inert plastic support) is generated in place by recirculating activated sludge from a municipal

Figure 72. New CPC collector developed under the CADOX project for photo-Fenton applications

treatment plant for a few days. Throughout the process, the pH must be kept between 6.5 and 7.5.

COLLECTION AND ENVIRONMENTAL RECYCLINGOF PLASTIC PESTICIDE CONTAINERS BY SOLAR PHOTOCATALYSIS (ALBAIDA)

In 2004, the final plant was installed and commissioned and preliminary evaluation was done [Blanco y col., 2004b, 2004h, 2004i, 2004j, 2004k; Malato y col., 2004 h]. The CPC solar photocatalytic plant consists of 4 rows of 14 identical modules (20 tubes/module, 2.7 m^2/module), each (total collector surface 150 m^2, photoreactor volume °0°6° L) mounted on a fixed platform tilted 37° wit respect to the horizontal (local latitude). System configuration is shown in Figure 73. Each row of 14 modules is connected in series and water flows directly from one to another and finally to the tank, each row independent from the other, by closing the entrance valve, but with the same pump. Each one of the 4 rows installed in parallel can be operated independently, by closing the entrance valve, although usually the whole system is operative. The system operates discontinuously by recirculation of the water by a tank (2000-L recirculation tank, 150 L in the cone and 15 L/cm in the rest) and a centrifugal pump. When the treatment of a batch of water from container rinsing is finished, it is returned to the washing system by another pump. This water is transferred to tanks placed for this purpose in the container-washing plant. When it is empty, the system is refilled with water from container washing and a pump installed in the container-washing bay pumps the water contained in the tanks above mentioned. Once the tank is full (or when the level so allows), the photocatalysis plant is filled. When the plant is full, the water is recirculated until it has the quality required, which is determined by analyzing samples taken in the sample valve installed for this purpose. In addition to what is described above, during treatment hydrogen peroxide is dosed. As the CPCs have a concentration factor of approximately 1, the system is outdoors and has no thermal insulation, the maximum temperature inside the photoreactor is 40°C.

To find out the best operating conditions for the plant, and any problems that could be related to water treatment, the following preliminary tests were made: Addition of a mixture of 6 commercial pesticides in water from washing acid containers (mostly nitric, sulfuric and phosphoric). The intention of this test was two. On one hand to demonstrate that the plant could achieve sufficient efficiency with "real" water from container washing. On the other, check that it was possible to set the initial pH required without adding H_2SO_4, but that the pH adjustment was attained from washing the empty acid containers, which are also recycled in the plant. The "real" water also contains solids in suspension coming from soil and dust stuck to the plastic, remains of labels, etc. Even though water is filtered, this does not remove most of the small particles. The solids in suspension make the water opaque, which is undesirable for light-absorption treatments.

Figure 73. View of the CPC collector field (150 m^2) installed in a plastics recycling plant in La Mojonera (Almería, Spain)

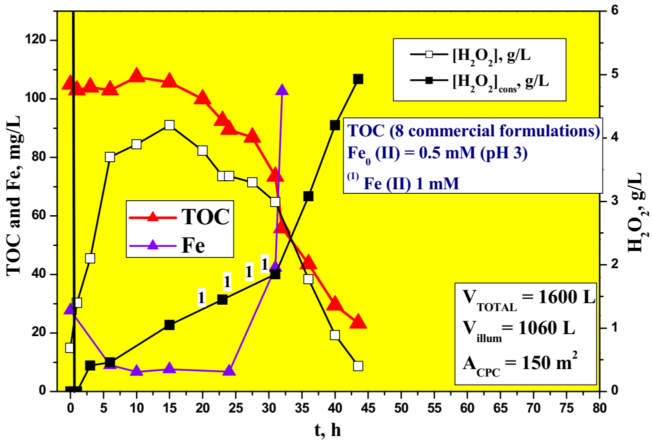


Figure 74. TOC degradation, hydrogen peroxide consumption and evolution of iron dissolved during a test with several different commercial pesticides at the Albaida plant

In the treatment shown in Figure 74 proper treatment was not achieved at first. As may be seen, there was no degradation of TOC for the first 22 hours of treatment. During this time, the the hydrogen peroxide consumption was also very low, which is consistent with the low degradation of TOC. In fact, the hydrogen peroxide was accumulated in the plant (concentration progressively higher), and it was necessary to stop its addition. On the other hand, it was also verified that the large majority of Fe added at the beginning was not dissolved (over 75% was lost). After observing this anomalous behavior, a detailed analysis was made of the water and it was found that there was a high concentration of phosphate (from washing the phosphoric acid containers, as there was none in the raw water).

The possible formation of insoluble iron phosphate is known [Wiszniowski et al., 2004]. This was demonstrated by filtering in a vacuum a known volume of treated water and redissolving at a very acid pH of solids retained in the filter. By analysis of PO_4^{3-} and Fe in that sample, the equimolar presence of both was found. Furthermore, by detailed calculation, it was found that all of the Fe that was not found in dissolution had preciptated. Therefore, it was decided to add perfectly known amounts of $FeSO_4.7H_2O$ (labeled "1" in Figure 74) in several batches and monitor the behavior of the dissolved Fe.

At the moment when all of the phosphates are eliminated from the water, the following amounts of $FeSO_4.7H_2O$ added contribute to the water the Fe necessary for the treatment. It can now be seen how starting at 25 hours, the concentration of Fe rises to nearly 100 mg/L, more than enough for the photocatalytic treatment to work. In fact, at that moment, the hydrogen peroxide consumption accelerates and mineralization of TOC also.

2) SOLAR DISINFECTION OF DRINKING WATER

It is even more evident that disinfection of water is a necessity that is absolutely basic to human activity since water is, in turn, the main vector of contagion of disease. This necessity is more or less solved in developed countries and in all of the large cities on the planet. However, the matter is far from being resolved in a large number rural environments of the so-called "developing" countries, which have a significant associated health problem. All of the indicators, furthermore, seem to indicate that the problem is going to grow in the next decades due to factors such as population increase and climate change, which noticeably accentuate problems associated with the scarcity or lack of water quality, impeding social and economic development even more in the most depressed regions of the planet.

It is precisely this lack of social and economic development that impede the implementation of infrastructures that can assist in solving or alleviating this problem. The methods that have traditionally been used to disinfect water are chemical flocculation, filtration in a granular medium and chlorination. Membrane filtration are very expensive, which impedes their generalized use for treatment of large quantities of water. Disinfection by adding chlorine (chlorination) is more commonly used, but requires the existence of a minimum infrastructure. That is why the development of simple, effective, completely stand-alone and economically feasible drinking-water disinfection technologies are of especial interest.

In this context, the PSA is presently undertaking several initiatives aimed at the development of a technology that makes it possible to disinfect water using solar radiation as the only source of energy. The activities carried out in this field in 2004 in the context of two European projects, SOLWATER and AQUACAT [*Fernández y col., 2004a,* 2004d, 2004e, 2004g] are described below.

SOLAR DISINFECTION OF DRINKING WATER (SOLWATER)
http://www.psa.es/webeng/solwater/index.html

The SOLWATER project (the formal title of which is "Cost effective solar photocatalytic technology to water decontamination and disinfection in rural areas of developing countries") is financed by the European Commission (Contract nº: ICA4-CT-2002-1000) under the INCO program (EC DG Research, Confirming the International Role of Community Research for Development). Its total budget is 1818.6 k€ and it is coordinated by the Environmental Applications of Solar Energy Group; its duration is 3 years (November 2002 to October 2005) with the participation of ECOSYSTEM-Spain, AOSOL-Portugal, Complutense University, Madrid, Spain, National Technical Univ. of Athens-Greece, Ecole Polytechnique Federale de Lausanne-Switzerland in Europe, and in South America Instituto Mexicano de Tecnología del Agua-México, Comisión Nacional de Energía Atómica-Argentina, Universidad Nacional de Ingeniería-Perú, TINEP S.A. de c.v.,México), since the potential application area for results is in Latin America.

The main purpose of this project is the development of a totally stand-alone solar system for the disinfection of drinking water in rural environments and without the use of any chemical additives [Blanco y col., 2004g; Sarriá y col., 2004b, 2004c]. The final system will treat water based on the combination of two photocatalytic processes activated by sunlight for the generation of highly oxidizing species that could be effective for the inactivation and elimination of pathogens in the water. The first of these processes is the use of titanium dioxide immobilized on an inert matrix to generate hydroxyl radicals ($^{\bullet}OH$) and the second is the generation of singlet oxygen ($^1O_2$) from a photosensitizer based on Ruthenium (II) complexes attached to a polymer matrix. It is also expected that the final system will also be able to eliminate potential trace recalcitrant organic pollutants that might be present [Augugliaro y col., 2004a, 2004b, 2004c; Di Paola y col., 2004; Fernández-Alba y col., 2004].

Figure 75. Prototype solar collector for water disinfection applications with catalyst fixed on a flat plate inserted vertically in the glass tube

For the development of this definitive system, several different prototypes were designed and built (see Figure 75) to be able to experimentally compare the behavior and efficiency of two different photoreactor concepts: one concentric with a tube inside a cylindrical reactor where the catalyst is attached and another flat one inserted vertically in the tube. In both cases, the optics used were CPC solar collectors with a 1 m^2 collector area. In turn, for each of these photoreactor concepts, two different catalysts were used: TiO_2 supported on a special paper developed by the Ahlstrom Paper Group (France) and Ru (II) complexes with polyazoheterocyclic ligands immobilized on polymer supports, a process developed by the Complutense University of Madrid. In 2004, these prototypes were tested with E. Coli as the reference to study the disinfection of the different systems [Duffy y col., 2004; Gill y col., 2004; McGuigan y col., 2004; McLoughlin y col., 2004a, 2004b].

Figure 76 shows some of the results obtained in the inactivation of E.Coli bacteria with Ru(II) immobilized on porous silicone compared to those obtained with KN47 paper containing 19.3 g of P25 TiO_2 per square meter surface. The experiment labeled as blank corresponds to KN47 paper but containing no catalyst, while the control tests performed under the same conditions but without solar radiation (systems covered to avoid receiving sunlight). As may be observed, the results obtained were very similar with both systems.

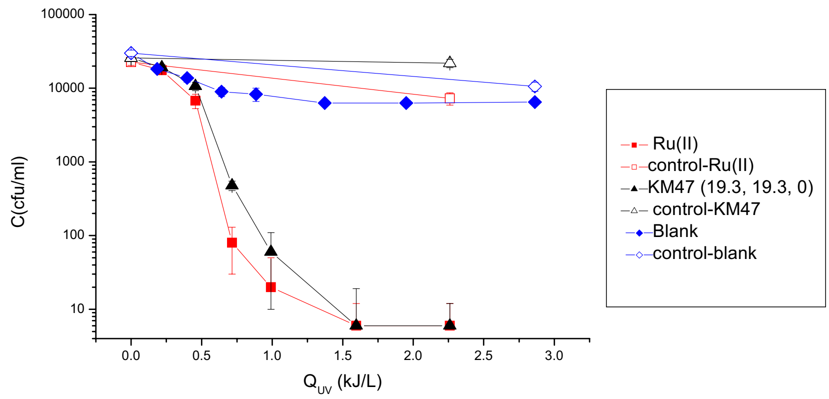
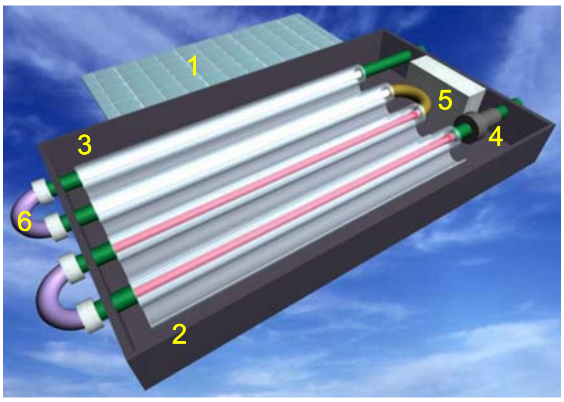


Figure 76. Disinfection activity of photosensitized Ru(II) complexes compared to Degussa P25 TiO2 supported Ahlstrom KN47 paper. The evolution of the concentration of E.Coli is shown over Q_{UV} (UV energy entering the interior of the photoreactor per unit of volume)

Final system design has been begun according to the experimental results obtained by the PSA and the other project participants (UCM, NTUA, EPFL and LACE) within the framework of the SOLWATER project, and it will be tested in 2005 in isolated rural areas in three different South American locations in Argentina, Peru and Mexico The results obtained in these 3 socio-economic environments at different solar latitudes will then be assessed.

DETOXIFICATION AND WATER PURIFICATION BY PHOTOCATALYSIS IN SEMI-ARID COUNTRIES (AQUACAT) http://aquacat.univ-lyon1.fr/

In addition, and linked conceptually to the SOLWATER project, the Solar Chemistry group also participates in another European project called "Detoxification of waters for



1. **Photovoltaic panel**
2. **Ru(II) photo-reactors**
3. **Supported TiO_2 photo-reactors**
4. **Pump**
5. **Electrical box**
6. **Easily opening to photo-reactors exchange**

Figure 77. Conceptual diagram of the definitive system developed based on 2 photoreactors for generating hydroxyl radicals by photocatalysis with TiO_2 and 2 photoreactors for generating singlet oxygen by photoexitation of Ru(II) complexes. A photovoltaic panel provides the power necessary to pump the water when there is solar radiation.

their recycling and potabilisation by solar photocatalysis in semi-arid countries" (AQUACAT, ICA3-CT2002-10016) coordinated by the University of Lyon-1. The goals of the AQUACAT project are basically the same as those of the SOLWATER project except that the region to which the final system is directed in this case is in the Mediterranean area. The final system here will be tested in communities in Egypt, Morocco, Greece and Tunisia. Figure 77 shows the final system concept to be developed and Figure 78 is a photo of the system built and prepared for testing.

Participants in the AQUACAT project are: univ. Lyon-1 (France, coordinator), CIEMAT-PSA (Spain), ECOSYSTEM S.A. (Spain), Ao Sol Lda. (Portugal), univ. Poitiers (France), Ahlstrom (Francia), Enig (Tunisia), Univ. de Fes (Marruecos), Projema, S.A. (Morocco), Photoenergy Center (Egypt), univ. Complutense (Spain), EPFL (Switzerland). The total budget is 1700 k€ with a contribution from the European Commission of 1000 k€. Project completion is scheduled for 2005.

Figure 78. View of the definitive system for testing Argentina (Comisión Nacional de Energía Atómica)

3) SOLAR SEAWATER DESALINATION

AQUASOL Projects HTTP://WWW.PSA.ES/WEBENG/AQUASOL/INDEX.HTML y SOLARDESAL http://www.psa.es/webesp/solardesal/index.html

In 2004, in the field of solar seawater desalination, activities were in the framework under two research projects, one European (AQUASOL Project: Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology) and the other national (SOLARDESAL Project: Advanced Hybrid Technology for Solar-Gas Desalination with Stationary Solar Collectors). Both projects have the same goals with the only difference that one is national with mush smaller scope and budget. The SOLARDESAL project was completed in 2004.

The entities participating in the SOLARDESAL project are: CIEMAT (coordinator), University of La Laguna, INABENSA and ECOSYSTEM. This project, which lasted three years, began in November of 2001 and was completed in 2004.

The entities which make up the AQUASOL Project are: CIEMAT (coordinator), INABENSA (Spain), Ao Sol Energias Renováveis (Portugal), National Technical University of Athens (Greece), INETI (Portugal), Cajamar (Spain), Hellenic Saltworks (Greece), Comunidad de Regantes Las Cuatro Vegas de Almería (Spain) and Weir-Entropie (France). This 4-year project, which began in 2002, is divided into two phases, a first research phase lasting two-and-a-half years, and a second demonstration phase, lasting a year and a half.

The common goal of both projects is the development of a hybrid solar-gas seawater desalination technology based on the multi-effect distillation (MED) process that meets the principles of energy efficiency, low cost and zero discharge [*Alarcón y col., 2004a, 2004b; Blanco, 2004d, 2004e*].

The AQUASOL Project in particular focuses on technological development of three basic points:

1) Incorporation of a source of hybrid solar-gas energy supply based on high-efficiency, low-cost compound parabolic stationary solar collectors (CPC).
2) Development of a double-effect absorption heat pump (LiBr/H_2O) optimized for coupling to the MED process, which reduces the energy consumption of a conventional MED plant to half.
3) Reduction of any type of discharge at all from the distillation process to zero by recovering the salt from the brine.

The research phase of the project was completed in 2004, which produced the final specification of the subsystems that make up the AQUASOL desalination plant (double-effect absorption heat pump, CPC solar collectors, thermal storage tanks, gas boiler and solar drier. Figure 79 shows the configuration chosen for interconnection of these subsystems. The first effect of the MED plant is fed directly with hot water at 66,5ºC from the storage tank, which is in turn fed either by the solar collector field, or by the double-effect absorption heat pump. Operation at those temperatures provides two clear advantages. In the first place, it considerably reduces the risk of crusting in the distillation plant heat exchangers, reducing the consumption of chemical additives, and in the second, energy efficiency of the stationary solar collectors is greater, the lower the difference in temperature between the fluid and ambient temperature. The purpose of connecting of the two storage tanks in series is to improve system controllability and maintain the temperature difference necessary for efficient heat pump operation.

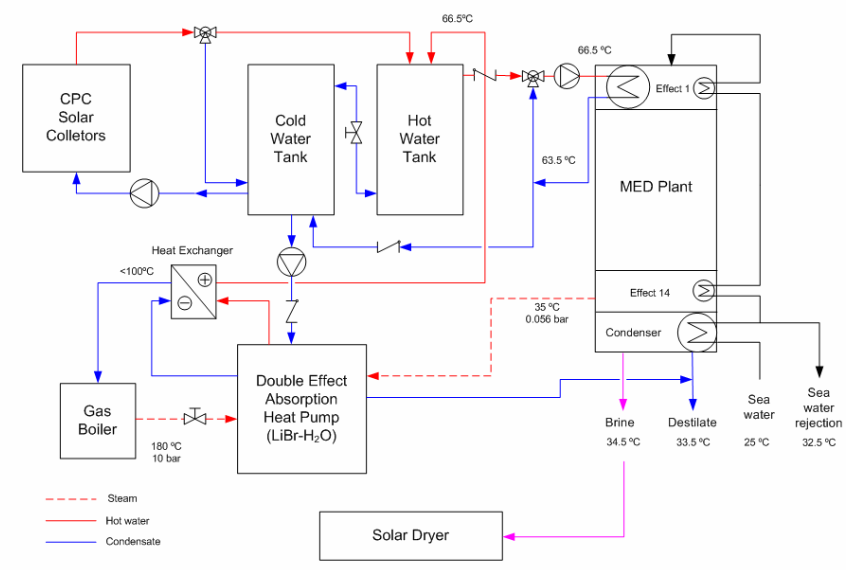


Figure 79. Final configuration of the desalination system to be implemented in the AQUASOL Project

Due to the limitation in maximum temperature with standard CPC solar collectors, the only possibility for operating the double-effect absorption heat pump is using high-pressure steam (180ºC, 10ºbar) prom the gas boiler. Therefore, the plant performance factor (kg distillate produced/2300 kJ energy contributed to the process) varies from 10 (solar-only mode) to 20 (gas-only mode). The project is going to study hybrid operation of the heat pump in combination with a contribution from the solar field to see whether it can function at partial loads (30-100%)[Hublitz y col., 2004].

Figure 80. Front view of the MED distillation plant building, with the two thermal storage tanks, the propane gas tank (right) and partial view of the water connection.

In the month of September the demonstration phase of the project began, the first tasks of which consisted of manufacturing and installing some of the above-mentioned subsystems. Figure 80 shows the two 12-m^3 storage tanks in front of the building housing the distillation unit, the propane gas tank to the right and part of the hydraulic subsystem that connects the two tanks and the distillation plant to the solar collector field.

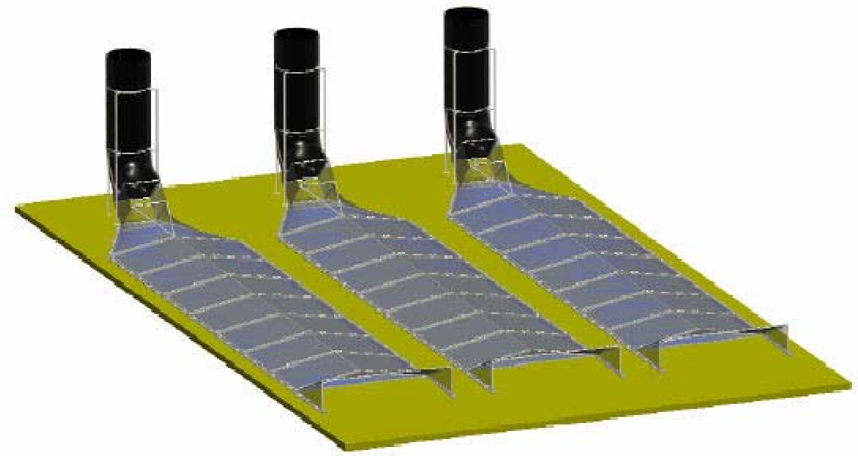
The solar field (see Figure 81), which is made up of 252 Ao Sol 1.12x stationary CPC solar collectors, has a total surface of about 500 m^2. The collectors are arranged in four rows of 63 collectors. Each of these rows is made up of modules of three collectors connected in parallel and these modules are in turn connected in series in groups of three. The oulet of the last of the three modules is connected in parallel to the row outlet into the header. The collectors are tilted 35° and oriented south[Blanco y col., 2004a].

The purpose of the advanced solar dryer is to increase the concentration of the brine produced by distillation up to the calcium carbonate saturation point (16°Be, Baumé scale). In 2004, a series of small experimental prototypes were evaluated at the INETI and National Technical University of Athens (NTUA) facilities, in which the influence of several different modifications in the preliminary design was studied. All of this finally led to the proposal of a final advanced solar dryer design that was installed on the Greek island of Lesvos in 2005 for evaluation during the AQUASOL Project demonstration phase.

This final prototype consists of three parallel evaporation channels (4 m x 17 m) connected to each other with a forced brine flow circulating through them. The channels are provided with a plastic cover, one section for preheating inlet air and a solar chimney at

Figure 81. AQUASOL plant CPC stationary solar collector field

the outlet to create convection pulling exhaust air out of the channels (see Figure 82). A fourth, uncovered channel is installed parallel to the other three to enable realistic comparison of the performance of the new prototype proposed. Orientation is north-south, because of the predominating winds in the final location where the prototype is to be installed. The proposed simulation models implemented predict an improvement 2.5 times the combined performance of open-air evaporation ponds at a salt plant.



Courtesy of INETI

Figure 82. Simulated view of the three advanced solar dryer modules proposed in the AQUASOL Project

4) CHARACTERIZATION OF SOLAR RADIATION

Activities related to the study and characterization of solar radiation in 2004 concentrated on projects related to:

- Measurement of solar radiation.
- Treatment of satellite images for calculating solar radiation.

The first of these activities has already been described in the section describing the PSA infrastructure. Action more relevant to the second of these lines of activity are described below.

The Plataforma Solar de Almería's meteorological station is located in a semi-arid climate at latitude 37º5'N, longitude 2º21'W and at an altitude of 497 m a.s.l, and is surrounded by the Sierra de Filabres mountains on the north, the Sierra de Gador mountains to the southeast and Sierra Alhamilla to the south.

The sensor signals are recorded every second and, from that data sample, the hourly averages are obtained. Wind speed and direction averages are obtained operating with both magnitudes together, after prior conversion to Cartesian coordinates.

This meteorological report was prepared from data collected at this weather station in 2004. The time given in the figures, is not the local time, but GMT. Values given are the averages for the months of January and July, as the most representative months of the winter and summer seasons.

SOLAR RADIATION

Figure 1 shows the monthly averages of hourly radiation. It may be observed that the highest average radiation is at midday during the summer months, June, July and August. Values are also high in April, although lower than these. The highest direct radiation in 2004 was **1080 W/m²**, was recorded at midday on March 2nd. The annual average of daily global radiation was **5200 W/m² day**: **2900 W/m² day** in January and **8370 W/m² day** in July.

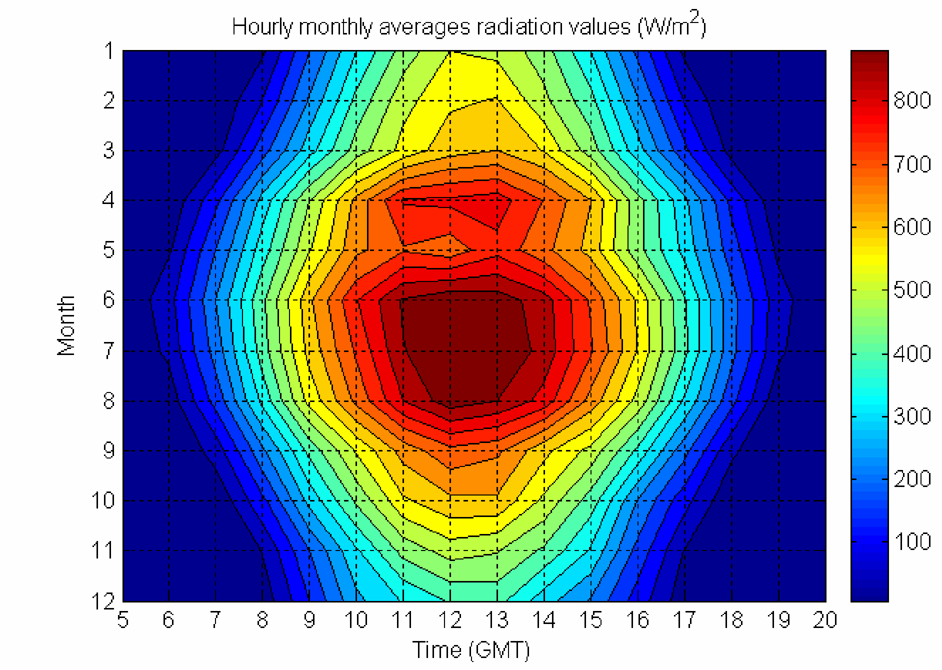


Figure 83. Profile of monthly averages of hourly global radiation

TEMPERATURE

Figure 84 and Figure 85 show the monthly average, maximums and minimums, and the profile of monthly hourly averages respectively. The maximum values recorded for temperature were **41.5ºC** on the 2-m-high sensor and **41.4ºC** on the 10-m-high sensor, both recorded after midday on August 24th. The minimums are, respectively, **2.69ºC** at dawn on March 2nd and **-0.78ºC** at the same time on December 28th. The annual average is **16.3ºC**, in January it is **11.3ºC** and July, **25.4º**C.

Figure 85 shows the inertia of high temperatures, which are prolonged into the afternoons in the summer months, especially in August. A steeper gradient in the change in temperatures at all hours during the transition seasons of Spring and Fall during the representative months of May and October, is also noticeable.

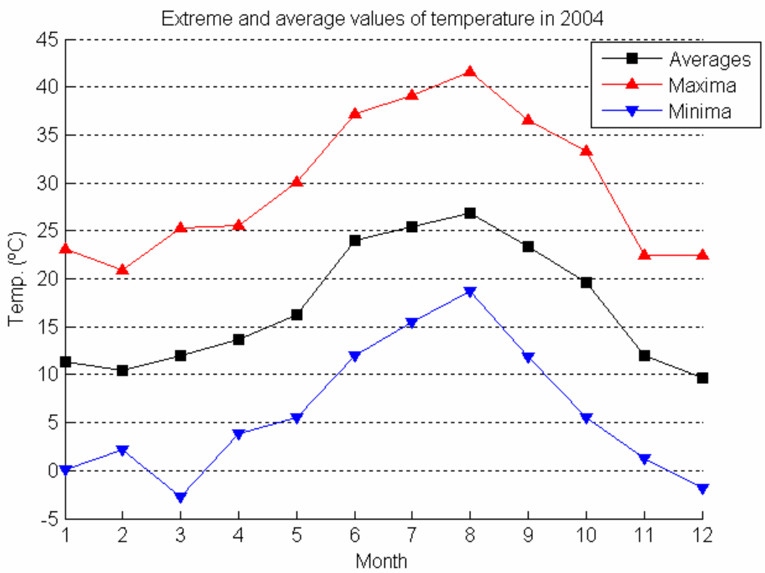


Figure 84. Monthly maximum, average and minimum temperatures.

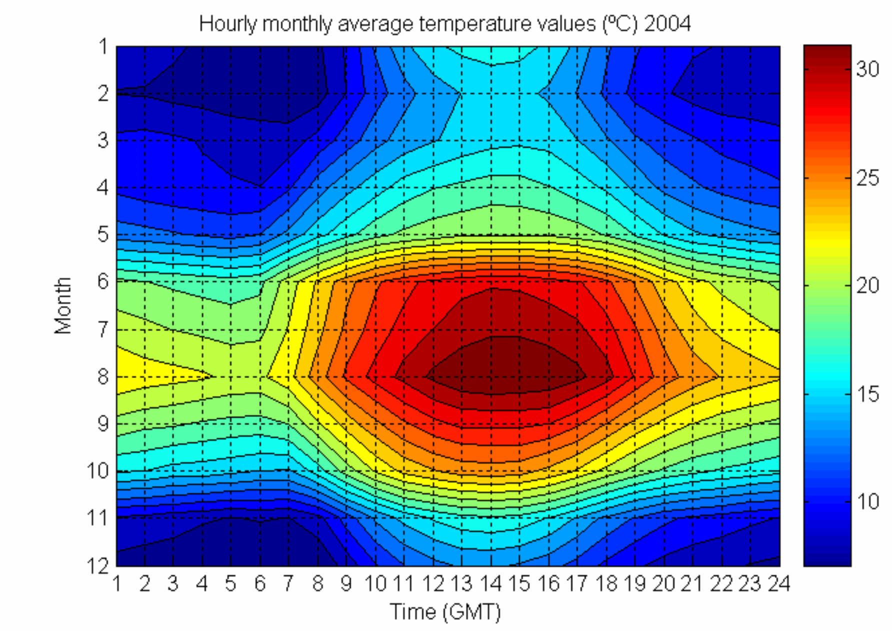


Figure 85. Profile of monthly averages of hourly temperatures

HUMIDITY

Figure 86 and Figure 87show the monthly average, maximum and minimums together and the monthly average of hourly humidity, respectively. Maximum values recorded were **93.3%** on the 2-m high sensor at dawn on March 20th and **95.5%** on the 10-meter-high sensor, recorded on the night of February 6th. The minimums are, respectively, 8.6% and 10.0%, both recorded on October 24th. The annual average at 2 m is **59**%; in January, **55.4**% and in July, **53.0**%.

Figure 87 shows that the lowest humidity is concentrated in the middle of the day during the summer months. It may also be observed that the first third of 2004 had higher general humidity than the rest of the year.

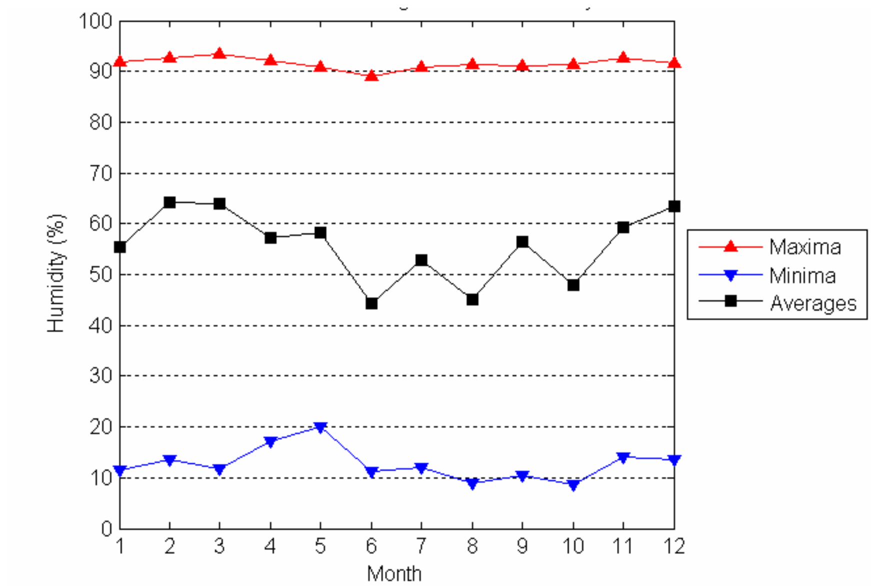


Figure 86. Monthly maximum, average and minimum humidity

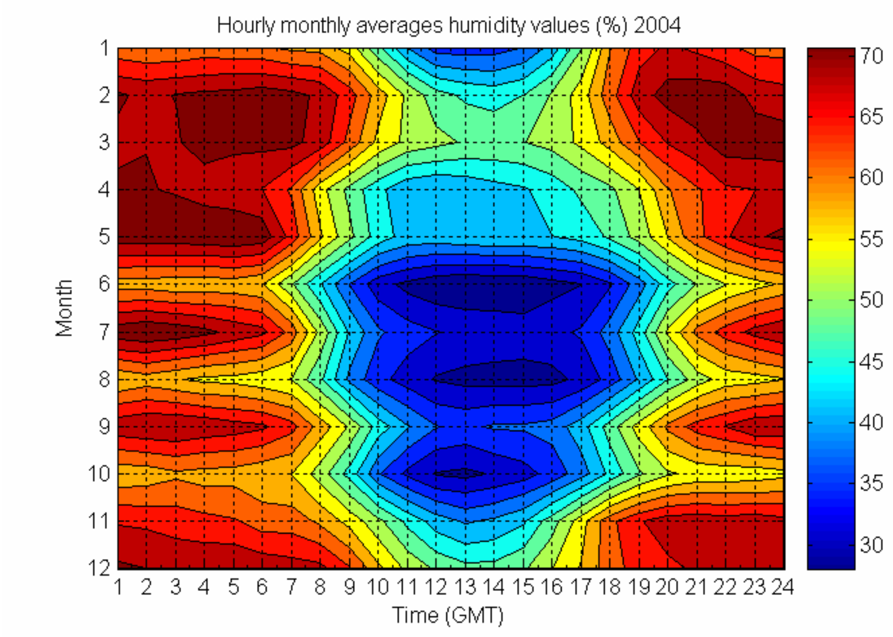


Figure 87. Profile of monthly averages of hourly humidity

WIND

Figure 86 and Figure 87show the average and maximum monthly wind speeds recorded at 2 m and the percentages of occurrence of wind direction. The strongest wind recorded was **22.1m/s** (79.6km/h) on the 2-m-high anemometer and **24.5m/s** (88.2km/h) at 10 m on May 5th, after midday. The annual average of hourly wind speeds in 2004 was **1.8m/s**.

The predominant wind direction was from the East 42% of the time in 2004 and the next most common wind direction was the Southeast, followed by West and Northeast, in this order. The predominance of these directions is attributable to the lay of the mountains that surround the PSA.

PRECIPITATION

In 2004, a total of 237 l/m² fell in the 50 days on which it rained. There was no precipitation recorded during the months of January and August. The rainiest months were March and April, in Spring. However, the month with the most rainy days was December. The day on which the maximum rainfall was recorded was April 9th, with **35.5l/m²**.

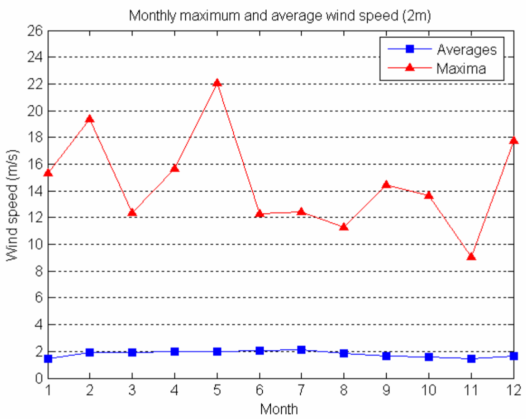


Figure 88. Monthly maximum, average and minimum wind speed at 2m.

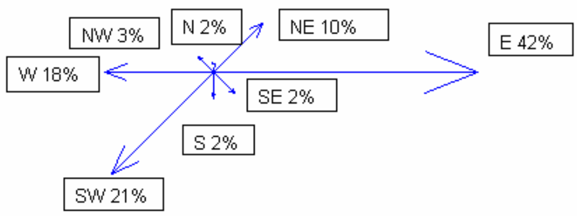


Figure 89. Percentage of wind direction

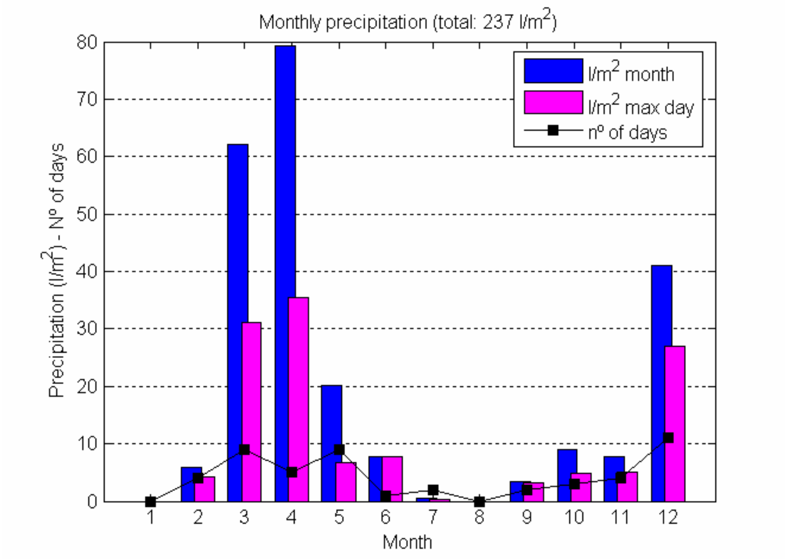


Figure 90. Monthly precipitation, with maximum rainfall and number of rainy days each month

ACQUISITION AND TREATMENT OF SATELLITE IMAGES

In the line of acquisition and treatment of satellite images, in 2004, action was concentrated in two specific projects:

- SOLSAT Project: Development of computation models to study on-grid photovoltaic systems. Statistical characterization of the energy resource.

  This 3-year (2002-2004) project is financed by the National RD&I Plan. The overall purpose of the project is the development and perfection of computation models for estimating the spatial distribution of solar radiation. It is intended to achieve models that enable determination of the spatial distribution of both global and direct solar radiation with accuracy in daily values of over 90%. This information is very much in demand at the present time, because of the nature of the environmental variable in itself and also because of its potential applications in solar energy exploitation. The methodology applied starts from with the collection, analysis and validation of data recorded at terrestrial radiometric stations, from which the best computation models for general application to the imaging window are determined. On the other hand, treatment of Meteosat satellite images is done using a series of primary images from the visible channel for a minimum of ten years and once the imaging window has been chosen, the treatment necessary will be selected to determine the variables related to solar radiation. From the simultaneous values recorded at the terrestrial stations and on the corresponding pixels from the satellite images, solar radiation inference models applicable to the entire image. Therefore, application of the models developed will provide results with a spatial resolution impossible to achieve with radiometric measurements. These objectives will be carried out by developing an information system that covers the following requirements: efficiently acquire and store the information received by the CIEMAT satellite image reception station in real time; manage satellite and pyranometric information; implement algorithms corresponding to the optimum computation models; analyze the different variables under study and view the resulting information. This system will be made up of a graphic user interface working in a Windows 95/98/NT/2000 environment and a database on a main server with the software necessary to handle large volumes of spatial dimension information.

- Solar Radiation Maps of Andalusia and Extremadura.

  The general purpose of this project, financed by the AICIA, is to map global radiation on horizontal-surfaces for Andalusia and Extremadura. To do this, satellite images are first studied, and a coefficient of cloudiness is computed for each pixel in the image. With this coefficient of cloudiness, models are fit using statistical regression and fuzzy logic techniques. Once the models have been fit, a new model for computation of the hourly global radiation in each pixel is implemented. The study starts out with 5 satellite images per day, from which 5 images of daily global radiation are computed. With them, an image of daily global radiation is obtained. Finally, 10 years of images from 1994 to 2003 are going to be worked with in this project, so a daily global radiation image will be obtained for each day in the ten years under study. With this series of images, a series of daily global radiation data can be studied for each pixel during this period and likewise, statistics calculated that we believe are representative of the total series (mean, median, etc.) in each of the pixels (corresponding to specific locations and in 5x5-km areas) as well as of the whole image.

5) OTHER ENVIRONMENTAL SOLAR RADIATION PROCESSES SOLAR ENERGY STORAGE WITH ENVIRONMENTAL IMPACT

In line with the problems mentioned due to use of fossil fuels and their prejudicial effect on the environment, one of the processes that offers the most opportunities in the mid-term, is the study of reactions that enable CO_2 to be transformed into substances with a greater energy content and that can be used as fuel. These processes would have the potential to enable continuous use of carbonaceous materials without contributing to a net increase in the amount of CO_2. This aspect is undoubtedly of interest given the growing environmental concern with regard to anthropogenic CO_2 emissions giving rise to the greenhouse effect [*R. Maestro y A. Vidal, 2004*].

In this sense, the application of the photocatalytic technology for promoting selective reduction of CO_2 represent a very attractive way to develop sustainable systems for production of organic chemical compounds, fuels and materials. Such processes would avoid the use of conventional fossil fuels and, thereby, the addition of any more CO_2 to the atmosphere.

Research done to date demonstrates that modification of the semiconductor by metals or metal oxides significantly affects their efficiency in this type of processes. Specifically, it has been demonstrated that ruthenium oxide facilitates transfer of gaps on the valence band, which are involved in the first stages of the H_2O oxidation process.

In general, the photocatalytic reduction of CO_2 causes small concentrations of a wide variety of C_1 and C_2 reduction products during the reduction processes that exchange 2-, 4-, and 6- electrons. It has been observed that the concentration of reaction products depends mainly on the pH of the solution and its composition. The results obtained to present yield energy performance values of 0.42% when working at basic pH and near 5% when the reaction takes place at acid pH (values calculated from the combustion heat of of the pure product). Although these are apparently low, it is should be mentioned that the net efficiency of solar energy to chemically storable energy in real systems is probably not going to exceed 12 to13·. This study is being performed with the collaboration of researchers at the CSIC Institute of Ceramics and Glass [*Vidal y col., 2004*].

Events

2004 was particularly intense insofar as activities of this type. In the first place, from the scientific point of view, the participation of PSA researchers in two 'solar community' congresses this year must be mentioned.

In chronological order, the first was the 'EuroSUN 2004' which took place in the sunny German city of Freiberg from June 22nd to 25th, and was organized by the European branch of the International Solar Energy Society (ISES Europe).

Later in the year, from October 6th to 8th, the '12th SolarPACES International Symposium on Solar Thermal Concentrating Technologies' took place in the Mexican city of Oaxaca. During this Symposium, the PSA and the University of Seville had the honor of being designated to jointly organize the next of these biannual symposiums, which will be held in Seville, from June 20-23, 2006.

Figure 91. Participants in the SolarPACES Symposium in Oaxaca

The PSA was well represented at both congresses, participating on their scientific committees in the organization, and intensely in the sessions through a multitude of papers and posters.

Local reference must be made to our participation with DLR in the '2nd Renewable Energies and Water Technologies Fair' from February 5th to 7th in the Palacio de Congresos in Aguadulce, organized by the Chamber of Commerce of Almería. Here the DLR and PSA-CIEMAT presented their research activities to the public in general through a stand where printed information was distributed and documentaries were projected.

Figure 92. The Plataforma Solar's Stand at the Renewable Energies Fair 2004

The organization of a European media event sponsored by the European Commission, which requested that the PSA host the event, was especially relevant. This event consisted of the preentation to the European communications media of various renewable energy research projects which receive financing from the 6^{th} Framework Program. Solar thermal energy (SOLAIR Project), tidal energy (WAVE DRAGON Project) and the geothermal energy (HOT DRY ROCK ENERGY) were represented. 47 journalists from communications media all over Europe, including 12 television channels, were at the event, giving considerable media impact to the PSA in general and to the SOLAIR project (coordinated by the CIEMAT with DLR participation) in particular.

Some of our existing collaboration received a definite boost with the signing of the international 'European Alliance of Solar Laboratories' convention by all the parties in an event organized by one of the partners, the CNRS-PROMES laboratory in Odeillo (France) on October $20^{th.}$ Coinciding with the signature, our PROMES colleagues organized a technical meeting called the 'EURO-SOL Forum: Power and Hydrogen from Concentrating Solar Systems'.

Figure 93. Pablo Fernández Ruiz, of the European Commission, addressing the media

Figure 94. Science journalists from all over Europe attend the event organized by the European Commission

In our facet as hosts reference must also be made to the 'International Conference on Solar Power from Space' (SPS'04). This conference, organized by the European Space Agency (ESA) was held in Granada from June 30^{th} to July 2^{nd}. Taking advantage of our geographical proximity, the organizers requested us to host the sessions on one conference day, July 1^{st}, when several presentations on concentrated solar energy were given and the participants had the opportunity to visit our facilities.

Especially memorable was the visit of a group of Portuguese students on September 25^{th}. The Portuguese Solar Energy Society (SPES) holds a national competition called 'Padre Himalaya' for primary and high school students. This competition consists of designing devices that make use of both thermal and photovoltaic solar energy. The prize was a visit to the PSA. We were proud to receive this enthusiastic group of students and professors and accompany them during their visit to our facilities.

Finally, we must mention the 2004 'European Grand Prix for Innovation Awards' received by our colleagues in the Solar Chemistry Group, Dr. Julián Blanco and Dr. Sixto Malato, in the category 'Grand Prix du Jury'. They accepted it in the name of the PSA at a ceremony which took place in Monaco, on December 11th. The photo below shows them at the awards ceremony with other winners.

Figure 95. 'Grand Prix du Jury' awards ceremony

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List of Acronyms

AOP	advanced oxidation process
ARC	Seibersdorf ARC Research Center
ASINEL	Asociación para la Investigación Eléctrica
BMSTU	Bauman Moscow State Technical University
BMU	German Ministry of the Environment
BOD	Biological Oxygen Demand
BOE	Boletín Oficial del Estado (Official State Bulletin) (E)
BOP	Balance of Plant
CASA	Construcciones Aeronáuticas S.A.
CCD	charge-coupled device
CEA	Commissariat for Atomic Energy (F)
CESA-1	Central Eléctrico Solar Almería-1
CHA	Spanish-German Cooperation Agreement
CICYT	Comisión Interministerial de Ciencia y Tecnología (E)
CIEMAT	Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (E)
CNRS	Centre National de la Recherche Scientifique (F)
COD	Chemical Oxygen Demand
CPC	Compound Parabolic Collector
CRS	central receiver system
CRT	central receiver technology
DCS	distributed collector system
DEAHP	double effect heat absorption pump
DER	Renewable Energies Dept. (CIEMAT)
DISS	Direct Solar Steam
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (D)
DSG	direct steam generation

EC	European Commission
EPFL	Ecole Polytec. Federale de Lausanne (CH)
ERDF	European Regional Development Fund
ETH	Swiss Federal Institute of Technology Zurich (CH)
EU	European Union
FID	Flame ionization detector
GC	gas chromatography
GC-AED	gas chromatography with atomic emissions detector
GC-MS	gas chromatograph coupled to mass spectrometry
HDPE	High-density polyethylene
HST	Hocheffiziente Solarturm-Technologie (High Efficiency Solar Tower Technology)
HTF	heat transfer fluid
ICP-CSIC	Instituto de Catálisis y Petroleoquímica – Consejo Superior de Investigaciones Científicos (E)
IEA	International Energy Agency
IHP	Improvement of Human Potential (EC)
INETI	Instituto Nacional de Engenharia e Tecnologia Industrial (P)
IPHE	International Partnership on Hydrogen Economy
ITC	Institute of Ceramics Technology de (E)
LC-MS	Liquid chromatography coupled to mass spectrometry
LECE	Laboratorio de Ensayo Energético de Componentes de la Edificación
LFC	linear Fresnel collector
MBB	Messerschmitt Bolkow-Blohm
MED	multi-effect desalination
MIMO	multivariable input-multivariable output
MPC	model predictive control
NTUA	National Technical University Athens (GR)
OPC	OLE for process control
PDVSA	Petróleos de Venezuela, S.A.
PROHERMES II	Programmable Heliostat and Receiver Measuring System II
PSA	Plataforma Solar de Almería
PSI	Paul Scherrer Institut
PTC	parabolic-trough collectors
PROFIT	National Scientific Research, Development and Technological Innovation Plan
SCADA	Supervisory Control and Data Acquisition Systems
SEGS	Solar Electric Generation Systems
SBP	Schlaich Bergermann und Partner
SENER	Empresa de Ingeniería SENER

SHIP	Solar Heat for Industrial Processes (IEA)
SISO	single input-single output
SODIS	Solar Disinfection
SolLAB	Associated European Solar Energy Laboratory
SOLUCAR	Solúcar Energía S.A.
SPES	Portuguese Solar Energy Society
SSPS	Small Solar Power Systems project (IEA)
STP	solar thermal power
TDC	temperature dependence curves
TOC	total organic carbon
TSA	Programa Tecnológico de Receptor Solar de Aire
UAL	University of Almería
UNED	National University for Education by Correspondence (E)
VOC	volatile organic compound
WFD	Water Framework Directive 2000/60/EC
WIS	Weizman Institute for Science (IL)
WTP	Water treatment plant
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (D)

Plataforma Solar de Almería
Carretera de Senés s/n
P.O. Box 22
04200 TABERNAS (Almería), Spain
Phone: +34 950 387900
Fax: +34 950 365300
e-mail: info@psa.es
web: www.psa.es