FINAL TECHNICAL PROGRESS REPORT

CONTRACT N° : **NNE5-1999-356**

PROJECT N° : **NNE5-1999-356**

ACRONYM : **PS10**

TITLE : **10 MW Solar Thermal Power Plant for Southern Spain**

PROJECT CO-ORDINATOR : **Solúcar**

PARTNERS :
Inabensa
Fichtner
Ciemat
DLR

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PROJECT START DATE : 01.07.2001 **DURATION : 54 months**

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Project funded by the European Community under the 5th Framework Programme (1998-2002)

1 Publishable Final Report

1.1 Executive Publishable Summary

1.1.1 Objectives

According to the **NNE5-1999-356** (5th Framework Programme) Contract with the European Commission, **PS10** proposal, **a 10 MW Solar Thermal Power Plant for Southern Spain** has very clear and defined goals. It is the objective of the project to design, construct and operate in a commercial basis a first-of-its-kind in the range of 10 MW solar CRS (Central Receiver System) plant producing electricity in a grid-connected mode. The PS10 plant should:

Achieve an annual electricity production about 20 to 25GWh

Validate the solar tower plant installed cost about 3000 €/kW_{gross} for the first plant.

Provide after tax IRR on equity higher than 7.5 %.

Produce electricity on a regular basis in the year 2006.

At the present stage of Central Receiver technology development, it is considered a key point the scaling-up to a first generation demonstration system operating in a commercial basis and with a nominal power in the range of 10-50 MW. It is the goal of the PS10 project to design, construct and operate in a commercial basis a first-of-its-kind 10 MW solar CRS plant (Central Receiver System) producing electricity in a grid-connected mode and based on saturated steam technology.

1.1.2 Description of the Work

The development of the project was originally planned in 6 workpackages that considered all necessary tasks for the plant promotion, financing, technological design, purchase of components, integration and start-up of the commercial operation.

During these works several important milestones for the Concentrating Solar Technologies, -CST-, were achieved. First project finance was signed with a bank for a solar thermal installation for commercial electricity production in Europe.

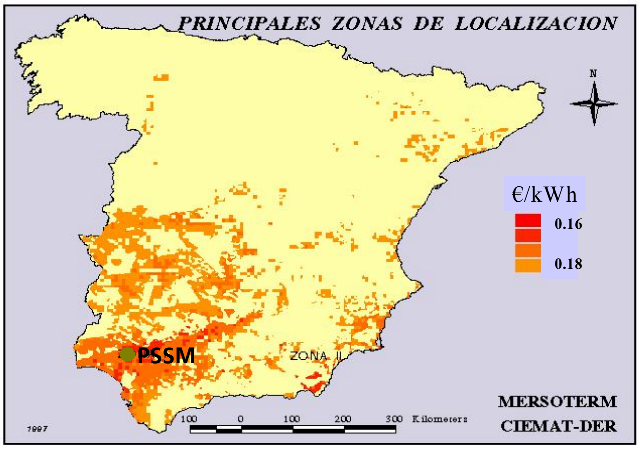
Two different approaches to the project were deeply studied during the technological development phase, in order to evaluate technical advantages and costs for these options. Special care was taken on selecting secure and proven technologies for every system, in order to maximize success options although penalising efficiencies and/or production performances.

Works in the project have ended with the construction of a 10MWe solar thermal power plant for electricity production and commercial operation.

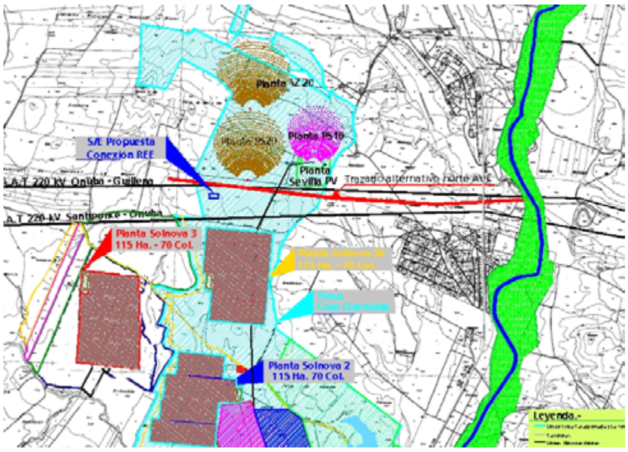
1.1.3 Results and Exploitation Plans

PS10 plant is located in the town of Sanlúcar la Mayor (37,2º Latitude), 25 km West from the city of Seville and is promoted by the company Abengoa through the already registered IPP Sanlúcar Solar S.A. It is placed in a property called Casaquemada. PS10 is the first of a set of plants to be constructed in the same area. All these plants will constitute the so called Plataforma Solar de Sanlúcar la Mayor, PSSM.

The Solar Platform at Sanlúcar la Mayor, PSSM, considers an ambitious plan for more than 300MW solar electric power generation by 2013 through different plants and technologies, both PV and thermoelectric, all placed together in an area of about 700Has.



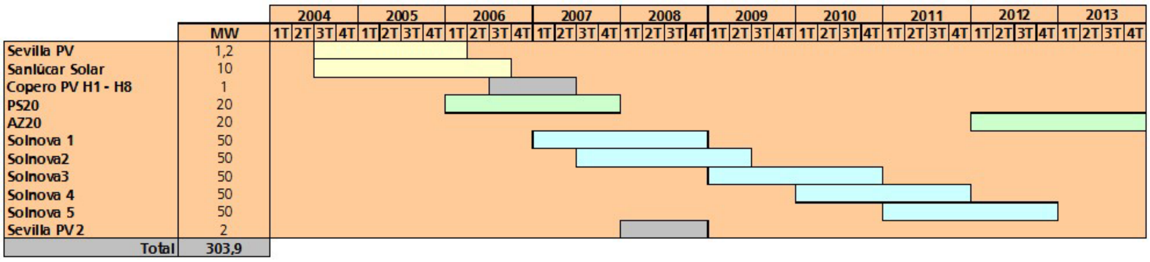
Location of PSSM in Spain, in one of the lower cost solar electricity generation areas because of high solar irradiation and availability of suitable land



The area selected for PSSM solar plants in Sanlúcar la Mayor is Casaquemada, a property traditionally exploded by Abengoa with agriculture

The plan for the more than 300MW electric power generation at PSSM facilities considers in addition to Sevilla PV (1.2MWp) and PS10 (10MW), two thermoelectric tower plants of 20MW, five thermoelectric plants of 50MW using some of them tower and some other parabolic trough technologies, and 2.0MWp new PV installations.

The construction of the first of these new plants, the solar tower of 20MW called PS20 has already started, and it is foreseen to be concluded by summer 2008. Construction of each of the other 6 plants and PV installations will be started in annual steps from 2007 till 2012, in order to finish the last of these actuations by the end of 2013.



Planning for the implementation of 300MW solar electric power at PSSM

PSSM has recently started operation with the commissioning and grid connection of the first of its facilities called Sevilla PV, a 1.2MWp photovoltaic plant considering 2 axis sun tracking systems, and double sun concentration on PV modules through mirrors arranged in a V trough concept. Sevilla PV plant, now into commercial operation, will generate over 2,300,000kWh a year through its more than 150 trackers of above 80m2 solar collection surface each, to be injected into the local grid.

A view of Sevilla PV 1.2MWp plant at PSSM in operation by April 2006

The second of the facilities to come into operation by 2006 is PS10, a solar tower 11MW gross power thermoelectric plant that will generate more than 23,000,000kWh a year by means of its 624 reflective heliostats of 120m2 surface each, and the 115m height tower were it is placed the solar receiver for steam generation to feed the steam turbine.

Aerial view of PS10 11MW solar plant

In reference to solar thermal central receiver systems, -CRS-, PS10 has confirmed to be a success regarding mass production of heliostats, development of updated control systems, innovation in optical evaluation tools, consideration of receiver concepts based on lessons learned in the past, and selection of the most reliable cycle options to be applied to solar thermal CRS based in previous experiences for saturated steam turbines and in floating pressure saturated water storage systems for small cloudy transients.

PS10 investment cost is about 35.000.000 €. The project has been granted with some public contributions because of its highly innovative features. In this sense, 5th Framework Programme of European Commission has contributed through DG TREN (Directorate General for Transport and Energy) to PS10 investment costs with a 5.000.000 € subvention. In the same way, the regional administration through the Consejería de Innovación Ciencia y Empresa in the Junta de Andalucía Autonomic Government has supported PS10 project with 1.200.000 €. PS10 has also financial support from low interest credit programs of Central Government through the Ministerio de Educación y Ciencia and its PROFIT program.

Economical feasibility for PS10 project is supported by Spanish legislation that foresee a solar tariff about 0,18€/kWh over pool market electricity price for –CST (Concentrating Solar Thermal)– plants, this results in an approximate selling price for solar thermal electricity of about €0,21 per kWh. Renewable regulations and solar premium are recognized in Royal Decree 436/2004 and some other later dispositions.

1.2 Publishable Synthesis Report

1.2.1 Background

PS10 is a 10MWe concentrating solar thermal -CST- power plant based on tower technology for grid-connected electricity generation in a commercial basis. Its construction has came real many years later from the last initiative to demonstrate the capabilities of the solar tower technologies, that was the erection of Solar Two, in Barstow-Cal, (USA) in 1994.

Various previous attempts have been approached earlier than PS10 to demonstrate solar tower technology feasibility. Some of these initiatives have been the Eurelios 0.75MWe project in Adriano (Italy), the CESA-1 1.2MWe plant at Almería (Spain), the Solar-One 10MWe plant at Barstow-Cal (USA), the Themis 1.0MWe plant at Targassone (France), the Sunshine 1.0MWe plant at Nio (Japan), the CRS-SSPS 0,5MWe plant at Almería (Spain),… most of them in the 80´s. Many of them were proposed in a hostile environment that couldn't offer enough support for surviving the continuous economical requirements for technology adjustments.

Technological research centers as Sandia NSTTF in Albuquerque-NM (USA), Weizmann Institute in Rehovot (Israel) and Ciemat-PSA at Almería (Spain) have became during many years the only evidence for technology feasibility demonstration. The active role that these institutions have played during second half of the 90´s and the first years of the new millennium working very close together to the companies for developing the technology in order to take it to a commercial status, has resulted essential for the actual industrial situation. Economical support politics to the renewable energies focused to CST in some countries as Spain, made the other part.

The official groundbreaking event for PS10 construction was held at plant site, the Casaquemada property in the limits of Sanlúcar la Mayor, on 28th of June, 2004. From that moment the period for plant erection started. A revision of the Renewable Electricity Generation Law in March 2004 improved in a significant manner the conditions for solar thermal electricity generation in Spain. Solar premium was raised 50% from 0.12€/kWh to 0.18€/kWh. Support of gas was allowed with the restriction of keeping its consumption (in energetic units) under 15% of the amount of electricity produced. Additionally, later in December 2004, the contribution of fossil fuels was allowed for consumption in solar thermal facilities to contribute on the generation of 15% of the annual electricity production. These new boundary conditions leaded to the final design and to the launch of the construction of PS10 solar thermal power plant.

PS10 project however has required a long promotion process till the present situation where erection is closed to finalize. PS10 project has its origins in a legal framework supporting renewable electricity generation through feed-in tariffs, issued by the Spanish Government in December 1998. Abengoa pioneered the first formal proposal of a solar thermal power plant in summer1999, after having defined the main parameters of the project. In January 2000, Abengoa through its subsidiary company Inabensa, together with Ciemat, DLR and Fichtner successfully applied for a 5.000.000 € subsidy to European Commission. The original project was based in the Phoebus volumetric air receivers technology.

Feed-in tariffs for solar thermal power were finally not considered for solar thermal electricity and this situation made the project not feasible in economical terms, requiring substantial modifications and a new formulation. In January 2001 Abengoa decides that the solar group working at Inabensa will form a new subsidiary company called Solúcar Energía, S.A., that takes the lead on project promotion and re-design. After a deep review of the volumetric air receivers technology previously selected and with detailed designs and economical offers of the air circuit supplied by companies like Babcock Borsig Power and Shell based in Phoebus technology and KAM (Kraftanlangen Anlangentechnic München), based in a modification of the Phoebus called Solair technology, it was not possible to achieve the technical and economical parameters required for the project.

By February 2003 Solúcar elaborated a new approach to the technology of the receiver for PS10 plant. Solúcar was aware of good results for saturated steam in previous experiences in receivers of solar tower plants, but found difficulties in identifying a good option to superheating the steam, as no good experiences were reported. Fuel backup and post-combustion to superheat the steam was also not possible since Spanish regulation did not allow the use of fossil fuels in production periods of solar thermal plants.

The saturated steam concept for solar receivers with heliostat fields had been successfully tested in several previous experiences, STEOR project (Solar Thermal Enhanced Oil Recovery) developed by ARCO in Kern County (California, US) in 1983, and the 2 MW receiver tested in 1989 in Israel by Weizmann Institute. In Spain, the most important reference was related to CESA-1 project at PSA-Almería, when the solar superheater was removed from its steam receiver, and it was converted so into a saturated steam receiver with a diesel boiler superheater. Good references and reports can be found on the operation and efficiencies of this system.

Therefore Solúcar found reliable the option of a saturated steam receiver working with a saturated steam power block and turbine for PS10.

1.2.2 Project Consortium

PS10 plant is promoted by IPP Sanlúcar Solar, S.A., a company 100% property of Spanish worldwide spread Abengoa, S.A. The EPC responsibilities in the project are leaded by Solúcar Energía, S.A., another Abengoa company working in the business of solar energy promotion. Technological support to the project is provided by an European consortium consisting of 3 companies and 2 institutes operating on the highest level of concentrating solar thermal, -CST-, technologies. Ciemat (Spanish center for energies development) and DLR (German aerospatial and energy development center) contribute to the project with concentrating solar know-how achieved in the long time operation of Plataforma Solar de Almería facilities. Fichtner (German engineering company with high experience in solar thermal plants design) and Inabensa (Spanish company belonging to Abengoa with high experience in solar installations) support the project from the manufacture and installation perspective. Solúcar is the consortium coordinator, with tasks related to project definition and promotion.

1.2.3 Main Scientific and Technical Goals

Main objective for PS10 project has been the erection of a 10MWe concentrating solar thermal power plant based on tower technology for grid-connected electricity generation and commercial operation years later from the last initiative to success in the solar tower technology with the erection of Solar Two (Barstow-Cal, USA) in 1994.

Many previous attempts have been approached earlier than PS10 to demonstrate solar tower technology feasibility. Some of these experiences in the past (Sunshine, Eurelios, Solar One, Cesa 1, Steor, Weizmann) were based in direct steam generation receivers, both for saturated and for superheated steam technologies. Other experiences approached the use of molten salts and liquid sodium in the solar receiver (Themis, Solar Two, SSPS-CRS) an others air (TSA, Solair). Technological approaches in direct saturated steam generation showed in general easier controllability than those based in superheated steam generation. Among the experiences in direct steam generation, several technological solutions were applied in the different projects, from natural convection (Sunshine and Steor in saturated steam receivers), to high forced recirculation for low saturated steam fraction (about 10%) generation (in Cesa1 and Weizmann receivers), considering also one-trough options for dry steam generation (Eurelios and Solar One receivers). The use of molten salts and liquid sodium in Themis, Solar Two and SSPS-CRS receivers showed technological feasibility, although problems related to high parasitic loads for electrical thermal tracing and to the daily processes for filling and emptying the receiver and ducts were also identified.

At the present stage of Central Receiver technology development, it was considered a key point for PS10 project the successful scaling-up to a first generation demonstration system operating in a commercial basis and with a nominal power in the range of 10-50 MW. It was considered the main goal of the PS10 project to design, construct and operate in a commercial basis a first-of-its-kind 10 MW solar CRS plant producing electricity in a grid-connected mode. For this objective, the selection of proven and low risk technologies was considered over some other approaches based in higher efficiencies. Wet steam generation with forced recirculation to feed a saturated steam turbine was identified as the option with higher options for success in this first commercial approach to the technology although this selection could mean the penalisation of some production efficiencies in PS10.

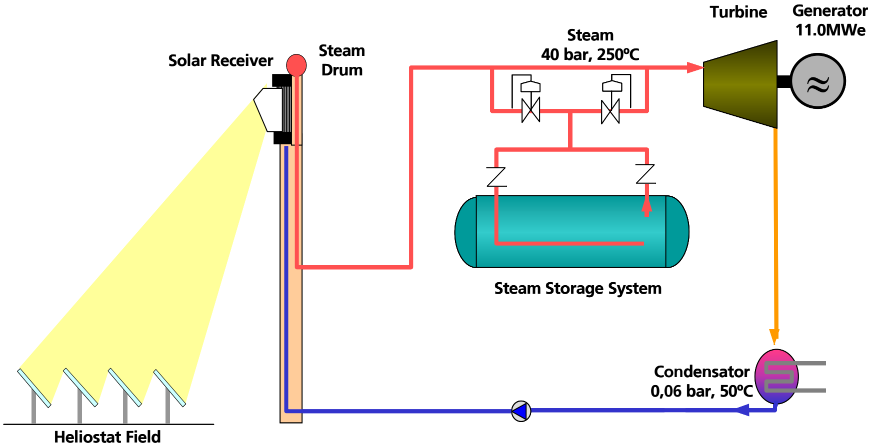
1.2.4 Description of Work and Main Results

PS10 is solar concentration solar thermal (CST) tower plant working with direct saturated steam generation (DSG) concept, at considerably low values of temperature and pressure (250ºC @ 40bar).

Some other design criteria taken into consideration for PS10 solar plant basic configuration has been related to solar multiple value and heat storage capacity for plant operation during no solar periods.

Spanish regulations don't allow hybridisation of CST plants out of the limits of 15% of annual generated electricity from fossil fuels. In this sense one of the key factors for a CST plant design is related to the decision of considering dailies shut-downs and start-ups of the steam turbine, or in the other hand, to consider huge storage capacity to cover at least in several months in the year (summer time) night periods in operation running the turbine from storage, reducing so the number of stoppages and cools of the turbine.

Keeping the general idea for not considering additional risky subsystems in its first commercial plant Solúcar decided to propose a small storage concept for PS10, assuming that starting and stopping the saturated steam turbine under controlled temperature conditions is a feasible operational procedure. Is for that than PS10 has been designed under an small solar multiple value, (1,3). This design allows the plant to dispose of the availability of a small stored energy capacity to deal with some short cloudy transient periods in order to protect the turbine and associated systems from overcame lacks of solar power that could damage equipments.



PS10 heliostat field is composed by 624 heliostats for a total reflective surface of 75.216m2. It is arranged in 35 circular rows around the tower. Each heliostat, Sanlúcar 120 type, is a mobile 121 m2 curved reflective surface mirror that concentrates solar radiation on a receiver placed on top of a 100 m tower. For this purpose, every heliostat is spherically curved so its focal point is at a distance equal to the slant range to the receiver.

Aerial view of the construction of PS10

Heliostat test onto the cavity of PS10

The Sanlúcar 120 heliostat is composed by 28 (7rows and 4 columns) curved facets manufactured with high reflectance mirror in order to provide the required optical properties to the heliostat field. Heliostat field has been designed using the latest calculation procedures and simulation tools with the objective of minimizing losses by cosine, shadowing, blocking, air transmittance and spillage effects. In this sense annual mean cosine effect in PS10 plant is over 81% and losses because shadows and blocks are not higher than 4.5% in annual basis.

Frontal view for Sanlúcar 120 heliostat

The high accuracy 2 axis sun tracking that is required for projecting sun disk image onto the receiver is provided by a mechanical drive guided by a local control system.

This local control system takes the responsibility of receiving sun position information from a higher control level that calculates sun azimuth and elevation values employing high accuracy correlations. It is also in charge of detecting heliostat current position and comparing it to the required to attack the receiver at a pre-selected aiming point. As a result of the integration of optics, mechanics and control, the heliostat is ready to concentrate solar flux on the top of the tower.

Tower design has been approached from the basis of reducing visual influence of such a big (120m total height) structure. For this purpose, the body of the tower is rather thin (8m) in the lateral view. Frontal view requires of about 18m to allocate 14m width receiver. A big open area has been proposed in the center of the body to achieve a lighter structure perception. An accessible platform at height 30m has been considered for visits, in order to provide a good sight of PS10 heliostat field lying in the north of the tower, and Sevilla PV plant (1.2MWe 2 axis tracking and 2x concentration solar PV installation) placed at the south. Construction was performed from August to November 2005.

Artist design and final view for PS10 tower

At the top of the tower is placed the receiver. The receiver is the system where concentrated solar radiation energy is transferred to the working fluid to increase enthalpy. PS10 receiver is based on cavity concept to reduce as much as possible radiation and convection losses. The receiver is basically a forced circulation radiant boiler with low ratio of steam at the panels output, in order to ensure wet inner walls in the tubes. Special steel alloys have been used for its construction in order to operate under important heat fluxes and possible high temperatures. It has been designed to produce above 100.000 kg/h of saturated steam at 40bar- 250ºC from thermal energy supplied by concentrated solar radiation flux.

It is formed by 4 vertical panels 5,40m width x 12,00m height each one to conform an overall heat exchange surface of about 260m2. These panels are arranged into a semi-cylinder of 7,00m of radius.

Three of four panels assembled on PS10 tower

During operation at full load, absorber panels will receive about 55,0MWt of concentrated solar radiation with peaks of 650kW/m2.

Flux measurements onto receiver surface are performed by a 2D array of calorimeters. Temperature onto receiver surface is also measured by a thermocouples matrix. Lectures of calorimeters and thermocouples are used not only for energetic calculation purposes but also as a reference for performance and alarms control.

PS10 saturated steam turbine assembled in powerblock workshop

Steam produced in the receiver is sent to the turbine where it expands to produce mechanical work and electricity. PS10 turbine operates at 250ºC and 40bar saturated steam conditions. At the exit of the turbogenerator unit steam is sent to a low pressure water-cooled condenser. Condenser exit is preheated with turbine extractions at low and medium pressures. Output of first preheater is sent to a deaerator, fed with steam from another turbine extraction. A third and last preheater is fed with steam from receiver. It increases water temperature till 245ºC. When mixed with returned water from drum, a 247ºC undercooled input feed to the receiver is obtained.

For cloudy transient periods, the plant has a saturated water thermal storage system with a thermal capacity of 20 MWh, equivalent to an effective operational capacity of 50 minutes at 50% turbine workload. The system is composed by 4 tanks that are sequentially operated in relation to their charge status. During full load operation of the plant, part of steam produced by receiver at 250ºC-40bar will be employed to load the thermal storage system. When energy is needed to cover a transient period, energy from saturated water will be recovered at variable pressure, from 40bar to minimum pressure allowed by the system to run the turbine at a 50% partial load.

The 4 thermal storage tanks of PS10

1.2.5 Assessment of the Results and Conclusions

Concentrating solar thermal is considered as one of the main options for renewable bulk electricity production. It is expected for the next years a concentrating solar thermal development similar in potential and magnitude to the wind power take-off recently experienced. Recent economic support measures that have been considered in countries like Spain are going to make possible the first steps for this concentrating solar thermal emerging business.

The first initiative of this new era is PS10 project. Its construction started on June 2004 and it is into service by 2006.

PS10 might be considered a milestone itself, as a whole, for solar CRS market penetration, since only one demonstration plant would be enough to proof the technology before starting commercialisation, and therefore should be followed by a series of fully commercial and competitive power plants with sizes of 20 -100 MW each.

A view of PS10 concentrating solar radiation in the stand-by position ready to aim the solar receiver