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Energy Procedia 49 (2014) 1820 – 1830

Energy

**Procedia**

SolarPACES 2013

## Solugas – Operation experience of the first solar hybrid gas turbine system at MW scale

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### Abstract

CSP hybridisation is one of the most promising concepts for cost reduction and dispatchability, and also one of the most competitive with conventional electricity generation systems. The Solugas project, first solar hybrid system topped with a gas turbine at megawatt scale, was commissioned in May 2012 in Abengoa's Solúcar Platform near Seville.

Numerous operation objectives of the project have been tackled since the operation started and the project is running for several hundred solar operation hours already, yet for the technology assessment the stable operation and evaluation of long time behaviour are crucial. In 2012 the maximum receiver outlet temperature objective was achieved: the temperature of the heat transfer medium -pressurised air- has been heated up to 800 °C in one receiver, reaching a temperature gradient of almost 500 K.

Current objectives include obtaining the tubular receiver efficiency accurately and optimisation of plant operation and control, in order to be able to characterise the behaviour of the plant and the production of the future plants.

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.

Final manuscript published as received without editorial corrections.

**Keywords:** CSP; Solar-hybrid; gas turbine; operation; efficiency measurement.

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## 1. Introduction

The Solugas project consists in the demonstration of a solar-hybrid power system with direct heating of a gas turbine's pressurised air. In combination with combined cycle systems, significant cost reductions for solar electric power generation can be achieved. The running demonstration project is the first megawatt-scale system that can be later offered to costumers in several configurations (combined cycle, cogeneration, etc.). The project is proving the technological feasibility, performance and cost reduction potential of the technology. A complete solar-hybrid gas turbine demonstration system, heliostat field and tower were built [1]. Previous experiences of the technology at kilowatt-scale can be found on the European research project Solhyco [2, 3]

Thus the motivation for the project is the introduction of the solar energy into a Brayton cycle which could also have a bottoming Rankine cycle, obtaining a solarised combined cycle (CC) power plant with highest conversion efficiencies. By heating pressurised air, the solar heat can be directly fed into the gas turbine without the losses of an additional heat exchanger. Additionally solar driven gas turbines do not require water for cooling and in the case of solar-hybrid combined cycle, water requirement can be reduced significantly in comparison to a solar steam power plant.

Since Solugas prototype commissioning, Abengoa Solar gained operation know-how, experiencing directly the solar Brayton technologies advantages and challenges, as well as the complexity of starting up and operating a large scale research plant. The special attractiveness of the Solugas project, apart from the development of the key components solar receiver and modified gas turbine, lies in the complexity of a successful integration of these together with all further components into a new solar tower power plant.

Furthermore three key objectives are defined, namely, operation at nominal regime - 800 °C and 10 bar -, accurate efficiency calculation, and optimization of operation and control, including stable operation, start up and shut down.

This paper describes in a short overview experiences gained during more than one year of Solugas operation, starting with a description of the plant, operation milestones and objectives, technology behaviour and improvements as well as the novel process developed for the receiver efficiency evaluation.

## 2. Facility description

Solugas started under the European Commission's 7<sup>th</sup> Framework Programme. In this project an international team consisting of DLR, Turbomach, GEA, NEAL and Abengoa Solar keeps working together introducing different expertise under the coordination of Abengoa Solar.

Figure 1 shows the main scheme of Solugas system. Pressurised air from turbine compressor is heated in the receiver, feeding the combustion chamber of a commercial Mercury<sup>TM</sup> 50 gas turbine modified to operate driven by solar energy. Here the air is heated further with natural gas to reach its nominal working temperature of 1150 °C.

The plant consists of a heliostats field of 69 units, each of them with a reflective area of 121 m<sup>2</sup>. The tower bears the receiver in a height of 65 m with an inclination angle of 35 ° from the horizontal axis. This allows minimising thermal convectional losses at the time that increases optical efficiency. The tower is already prepared to test future hybrid concepts. Figure 2 shows a picture of the plant in operation. Heliostat field, tower and point focus on receiver are shown.

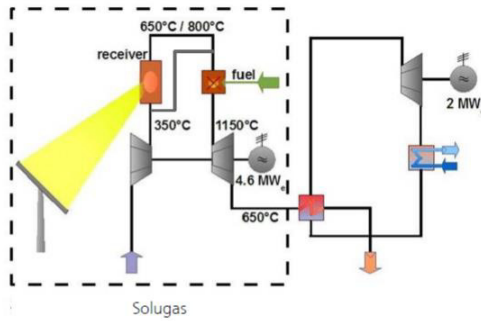


Fig. 1: Solugas cycle scheme (inside dashed line)



Fig. 2: Solugas plant under operation

The Solugas high temperature receiver has been proved to heat pressurised air up to 800 °C. It is made out of 170 fine nickel based alloy absorber tubes. Air from the gas turbine compressor is directed towards the receiver, being guided at first instance in a front ring and from there distributed into all the absorber tubes. The air is later collected in a back ring and finally led to the gas turbine. Part of the compressed air is led through a bypass to increase the operation flexibility and test conditions. Several hundred sensors are used to monitor the plant behaviour: For the compressed air flow the receiver temperature, mass flow and pressure are continuously measures, having alone 225 thermocouples to monitor the temperatures on the material and inside the pressurised air flow.

The absorber tubes are exposed to high concentration of solar irradiation, achieving in 5 m of irradiated length a temperature increase of more than 500 K. Thermal expansion is a critical issue that is minimised with a bellow system. Figure 3 shows the receiver just after being placed on the tower.

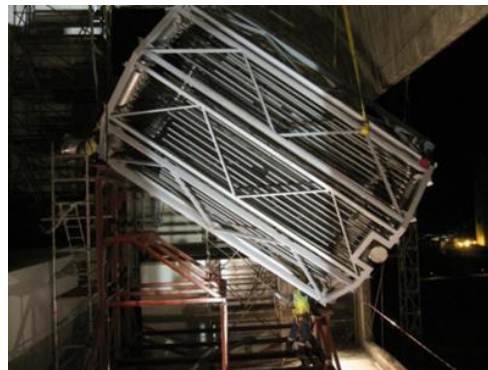


Fig. 3: Solugas receiver placed on tower

A modified Mercury<sup>TM</sup> 50 gas turbine generator set manufactured by Solar Turbines Incorporated is used in the project. Major modifications were carried out to adapt the unit to solar energy applications. They include hardware aspects as the removal of the recuperator, the modifications of the ducting connections and the combustion system as well as a wide range of control modifications, implementing new and modified operation controls, protections and tools to predict transient period's performance, overspeed risks and durability supervision among others.

Receiver insulation plays a significant role in Solugas. In Figure 3 the receiver is not encased yet by the insulation system which has the responsibility to keep the hot temperatures arranging a cavity shape favouring thermal efficiency. Insulation is made of ceramic fibres and supported with metallic plates prepared to bear with thermal expansion in the receiver.

Further information about the facility can be found on [1] and [4].

### 3. Operation and achievements

The works at Solugas plant aim to achieve a double objective. First, to operate a solar hybrid plant at megawatt scale under several scenarios which include stable conditions, transitory effects and emergency shutdowns, which can be considered as standard plant control. Second, to work at a wide range of working conditions, including receiver outlet temperature, mass flow, pressure and turbine load, to determine system efficiency and receiver characterisation. Solugas plant has been in operation since July 2012 under these two strategy ways, summing up nearly 800 working hours when the paper was written.

Regarding standard controls, the first task was to achieve an ideal focus of the heliostat field on the receiver cavity which is significantly smaller in aperture than in other plants, just 2.7 m of diameter for a field of 69 units, each of them with 121 m<sup>2</sup> reflective area. The reason is the general scale of the prototype as well as the cavity shape arrangement to minimise convectional losses. Therefore on one hand heliostats need to be controlled very accurately to avoid spillage losses and very high concentration of radiation in particular areas of the receiver. Additionally, as one of the major advantages of the presented technology is a very rapid starting up process, thermal gradients when increasing temperature have also to be regulated to avoid unnecessary material stresses.

With current experience it has been demonstrated that the plant can be fully operative in 30 minutes at a desired receiver outlet temperature. This offers totally new operation possibilities and flexibility in comparison to steam plants where it is strongly recommended to have a relatively slow heating up process to avoid fluid hammer. Pressurised air does not face such a problem. The gas turbine itself can be started and running at full load in even less time of approximately 10 minutes.

The operation behaviour during transients represents another advantage of hybrid technologies as it enhances the dispatchability against other similar competitors. Nevertheless plant control present a challenge in certain cases to reduce the thermal gradient on the tubes, as an optimal life span of the components has to be taken into consideration. A 360° dome camera on top of the tower helps to predict changes on DNI. Figure 4 shows the plant response to transitory clouds when operating at 600 °C as receiver outlet temperature. DNI drops and rises from 850 – 900 W/m<sup>2</sup> to nearly 0 W/m<sup>2</sup> up to five times in one hour. It can be seen that the temperature in the receiver also decreases and increases rapidly in connection to the DNI. Meanwhile the power output is kept constant. Thermal gradient is found to be up to 90 K per minute.

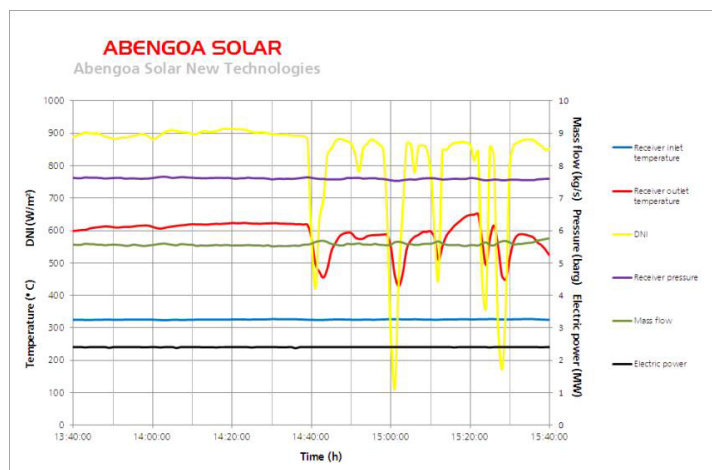


Fig. 4: Operation under transient periods keep electric output constant

Emergency or sudden shut down, followed by immediate start-up have also been carried out caused by alarms due to component malfunctioning or simply to test system response at adverse conditions. Next graph shows a representative example of a sudden shut down. Turbine is stopped and temperature drops immediately. This was considered in the design of the receiver and does not affect its characteristics. The line that corresponds to temperature shows a thermal gradient about 50 K per minute. However in some cases even thermal gradients of 100 K per minute have been measured, although it has not been found to be common.

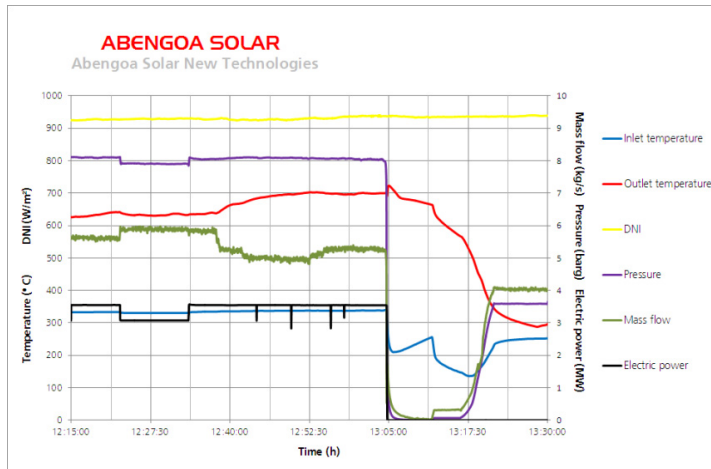


Fig. 5: Sudden turbine shut-down and temperature rapid decrease

In order to characterise the receiver, to measure the receiver efficiency and system performance, Solugas plant is under operation at different working regimes, including receiver outlet temperatures from 400 to 800 °C, receiver mass flow from 3.5 to 5.75 kg/s, system pressure from 3.6 to 8.8 barg and turbine load from idle mode to 4.5 MWe.

Figures 6 and 7 show two significant milestones achieved during the project. The first one presents the first day that receiver outlet temperature reached 800 °C. Maximum temperature of the pressurised air was kept during 15 minutes and temperature was over 700 °C during two hours. The second graph presents stable conditions obtained for receiver measurement efficiency for receiver outlet temperature of 700 °C.

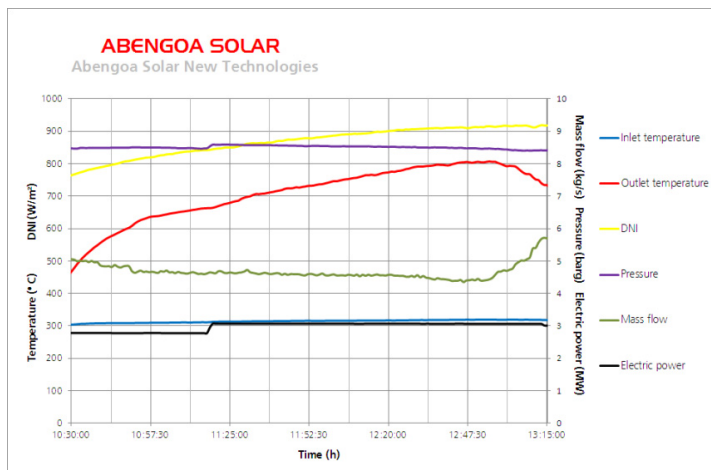


Fig. 6: First day operation at 800 °C as receiver outlet temperature

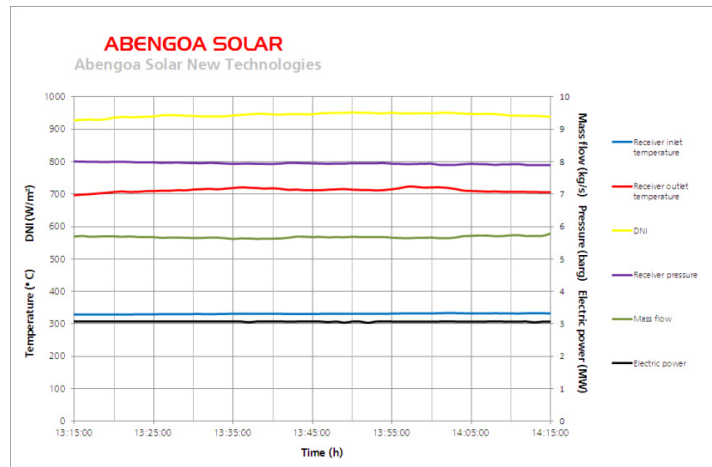


Fig. 7: Stable operation at 700 °C as receiver outlet temperature

#### 4. Components performance and modifications

During operation the components have been monitored in order to obtain maximum information on their performance and options for improvement.

##### 4.1. Heliostats

Heliostats include an innovative tracking system using hydraulic components for both, azimuth and elevation movement. During operation the heliostats as well as their control system have been tuned so the focusing to the aim point at the cavity entrance was reached more accurately and tracking the sun has become easier, and smoother. Some of the improvements have included new connection systems on both azimuth and elevation movements that enhance the heliostat performance.

##### 4.2 Receiver

The solar receiver absorber tubes are exposed to high concentration ratios. Plant operation and control have been improved, therefore even if thermal gradients between the in- and outlet of the tubes are in the range of 500 K, solar flux distribution has become more homogeneous on the absorber tubes, reducing temperature difference between the different regions of the receiver to a minimum. As this helps to reduce the maximum temperatures in individual tubes, it is a major achievement considering that still the metallic parts are bearing maximum temperatures over 850 °C to keep the pressurised air temperature at 800 °C.

In order to avoid undesired thermal expansion on the tubes, a bellow system is designed and manufactured. The good performance of the controlled absorption of the axial extension of the tubes by the bellows is essential for the lifetime of the receiver. Based on the operation experience the bellow design has been improved and tested, including a support that retains straight the bellow in the original position.

##### 4.3 Receiver insulation

To preserve hot temperatures inside the cylindrical shaped arrangement of the receiver, thermal insulation plays a key role. It has to minimise thermal losses and the shape is optimized to achieve the maximum contribution on a homogeneous temperature distribution and low gradients of the absorber tubes. The insulation material is mainly made by a ceramic fibre which is directly exposed to solar concentration and temperatures that surpass 900 °C. On the outside, this material is covered by a stainless steel layer that keeps it fixed and protects the external regions.

Significant thermal gradients as well as exposition to ambient conditions while the plant is not under operation have a certain negative influence on the insulation performance. Those areas where the hot receiver parts are joined to the cold metallic structure that supports it were found to experience degradation after some operation time. To avoid high temperature on the joins and keep them insulated, a new system for protection was implemented. Figure 8 shows the poor performance of the initial insulation around one join and figure 9 shows an improved join protection.

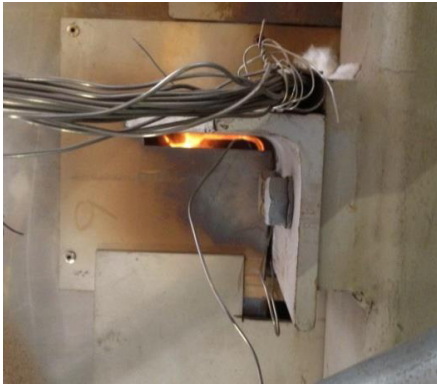


Fig. 8 : Poor insulation performance on join between receiver and support structure and a bundle of thermocouples leaving the receiver cavity



Fig. 9: Join totally insulated with improved fixing system and wires.

#### 4.4 Gas turbine

The gas turbine Mercury<sup>TM</sup> 50 is successfully operating in the different operation modes of the solar plant. Due to the adjustments the turbine needs to be able to work in a wider range of conditions than in the commercial configuration. Further, the selected site for the prototype plant in south Spain is ideal to test the technology, as a wide range of meteorological conditions can be found, reaching from extremely high ambient temperatures as can be found in desert areas to colder seasons with transient periods and from very low to high humidity. The turbine needs to guarantee stable operation and ramp up behavior under each condition, which was achieved by optimizing the control system and turbine parameters.

Optimization of the control and consumption of the gas turbine is achieved by controlling the turbine's combustion chamber and injectors' temperature as well as regulating the compressor guide vanes. Also better regulations of the pilot and main valves to decrease the natural gas consumption and the stability of the turbine have been implemented.

The turbine's combustion chamber is prepared to admit 650 °C as maximum inlet temperature. Therefore the temperatures are monitored to avoid miss functioning of the turbine.

## 5. Receiver efficiency measurement

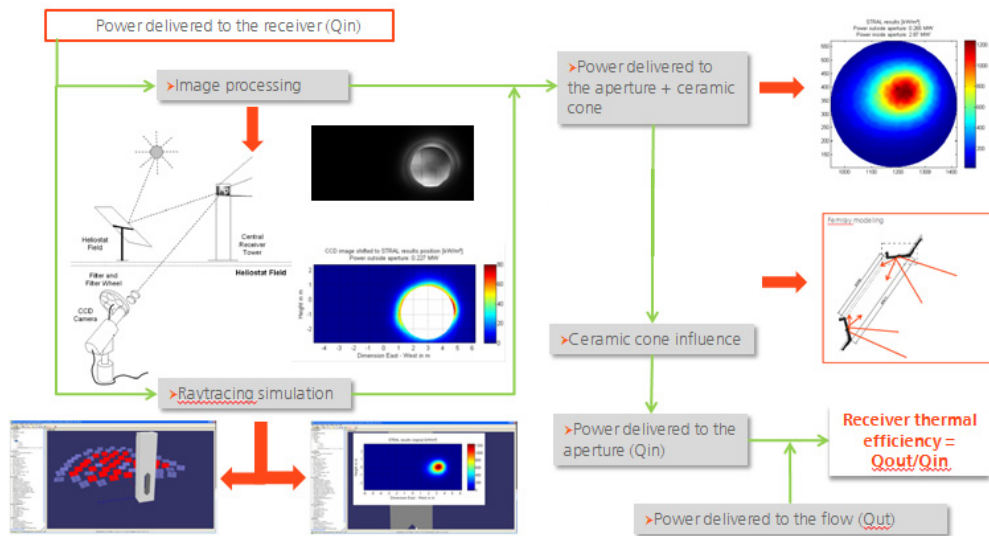


Fig. 10: Schematic representation of evaluation process

### 5.1 General

The efficiency of the receiver is defined by the quotient of solar input and thermal output power where thermal power is calculated by measured mass flow and temperatures. The novel technique chosen to determine solar input is based on a state-of-the-art method using indirect optical measurements with a CCD camera, a target and direct flux sensors for calibration [5]. The method uses ray-tracing simulation supported by indirect measurement. But instead of a special painted target with Lambertian properties the front protection is used as reflecting surface. Not flux distribution in the receiver aperture but around it (spillage) is measured with the camera. In parallel the flux distribution is simulated with ray tracing and results are compared with the taken image. Using a coincident simulation, solar input power into the receiver can then be determined. Pre-studies and tests with this approach showed promising results [6].

### 5.2 Measurement equipment

The system is equipped with more than 400 sensors that ensure secure operation, controlling and evaluation of the system. Among them a pitot tube as mass flow measurement device and thermocouples in inlet and outlet of the receiver for temperature measurement are installed. For solar flux measurement radiometers and a CCD camera positioned in the heliostat field in the optical axis of the receiver are used.

### 5.3 Evaluation tools

For the simulation of the flux distribution a fast tool for high-precision simulation of Heliostat Fields (STRAL [7]) was chosen. Input data are mainly measured values like direct normal irradiance (DNI), reflectivity of the heliostats, topographical measurements of the heliostat field and the tower and deflectometric measurement of the mirror of the heliostats. Some values like sun shape and tracking error are not exactly known and needed to be assumed. Thermal evaluation and processing of the CCD images are both done in MATLAB®.



### 5.4 Operation

To determine the receiver efficiency for different operation modes tests at different temperatures, load, pressures and operation condition like DNI and wind were realized. The different temperature levels in the receiver outlet during the tests varied from 400°C to maximum conditions in 100K steps. An example of a tests day at 600°C is shown in figure 11. Operation was controlled to achieve stable conditions 2.5 hours before and after solar noon. Images of flux distribution were taken in short intervals during stable operation. Achieving extremely stable conditions during an extended period, in order to reduce the uncertainties of the measurements, was one of the main challenges of operation and was achieved after gaining experience by the operating team as well as improvements in the solar field and control.

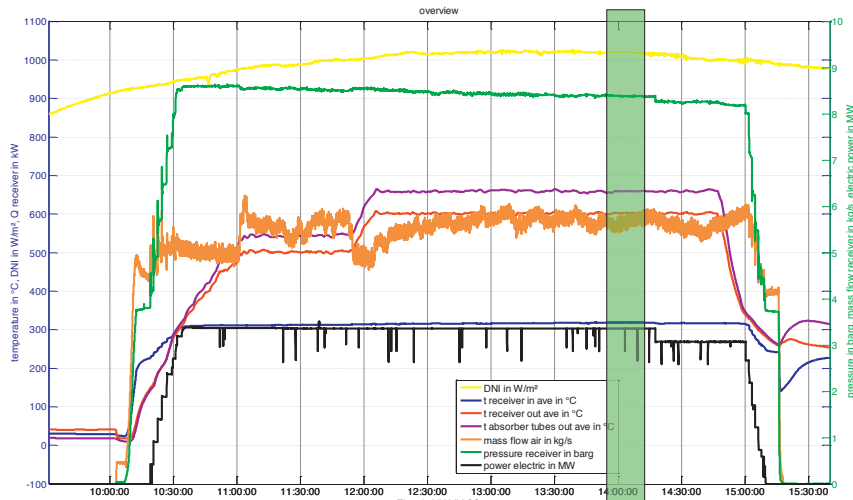


Fig. 11: Plot test overview exemplar test day (temperatures, DNI, mass flow, turbine load)

### 5.5 Work flow

Directly after a test, thermal evaluation of data is done to check steady state criteria of the system. Stable measurement ranges of 10 minutes (green marked frame in figure 11) are chosen and thermal gain, average values and uncertainties calculated. A flux image taken at the end of the selected range is calibrated and processed. For calibration, the raw image with grey values (Figure 12) is multiplied by a calibration factor to convert the image in a flux map in kW/m<sup>2</sup>. Main focus of the image processing is the correction of the non-homogenous surface of the front protection. This is done by a background correction matrix considering different reflectivity values of the surface. In a last step, filters are used to eliminate artifacts in the image. Figure 13 shows the calibrated and corrected image.

Additionally, the incident power at this measurement point is simulated in STRAL. The result is a simulated flux map in the front protection plane where the inner part of the aperture is cut off and the remaining simulated spillage (shown in Figure 14) is compared with the corrected image. The coincidence of the integrated power and the flux density distribution together with a low root-mean-square deviation (RMSD) value between simulated and measured flux are indicators of quality of the simulation. A parameter variation of the simulation is done changing mainly tracking errors and aim points as they are the values with mayor uncertainties. Several runs are compared and the best fit selected. The input power is then calculated by integration of the flux density over the aperture circle plotted in Figure 15.

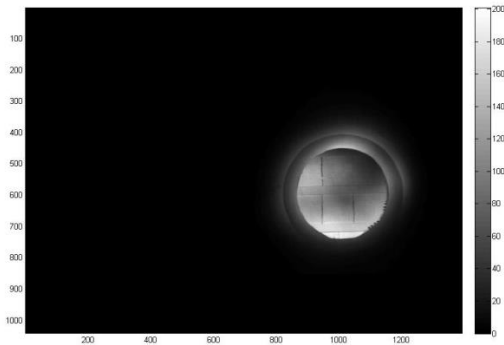


Fig. 12 raw image (grey values)

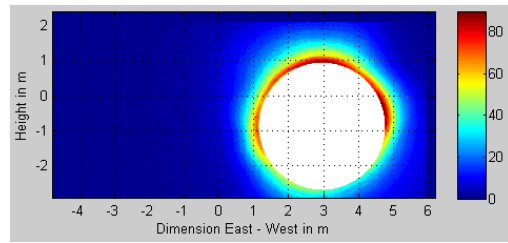


Fig. 13 calibrated and corrected image

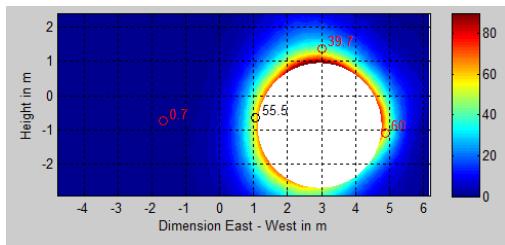


Fig. 14 Results from STRAL where flux density distribution and integrated power matches the best the CCD image

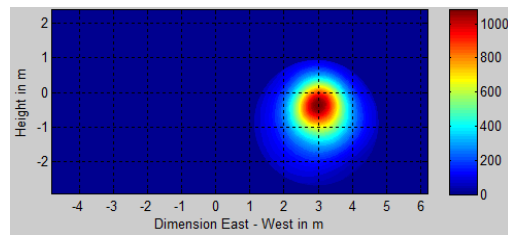


Fig. 15 Flux map on receiver aperture

## 6. Conclusions

Solugas plant, the first solar hybrid solar plant with solarised gas turbine at megawatt scale has been operated during one year under a wide range of conditions, including standard working regime for commercial plants and specific situations in order to obtain accurately its efficiency and characterise the solar receiver. It is made out of 170 nickel alloy tubes and heats pressurised air up to 800 °C.

The whole system has proven to perform correctly under nominal and adverse conditions. Nevertheless experience has provided extensive knowledge on operation, control and component pros and cons, which is contributing to improve in every aspect the plant in particular, and the technology in general.

## 7. Future work

Further improvements and modifications on the operating system are foreseen to be implemented during the on-going operation of the plant. Additionally the Solugas facility is already prepared for the integration of a volumetric receiver in order to further rise the pressurised air outlet temperature up to 1000°C and increase the solar share.

In addition to the receiver, the facility is prepared to incorporate new research programs, regarding concept design, storage, turbine improvements and receiver distribution. All these developments combined will allow to gain experience and to achieve a commercially available full solar hybrid technology competing with renewable and conventional power plants thanks to the ability of providing dispatchable energy with reduced water and gas consumption.

## Acknowledgements

Abengoa Solar on behalf of the entire Solugas consortium would like to thank the European Commission for its commitment and support of the project with grant TREN/FP7EN/219110/”SOLUGAS”.

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