THE 480 kW_P EUCLIDES™-THERMIE POWER PLANT: INSTALLATION, SET-UP AND FIRST RESULTS

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ABSTRACT: The D.C. section of the 480 kW_p EUCLIDES-THERMIE demonstration plant, the world largest using concentration and the first subsidised by the European Commission, was completed on November 27th, 1998. One inverter, connected to a pair of arrays and injecting power into the grid, was already operative by that time. Currently a monitoring station and seven inverters, one per each pair of arrays are operative.

The EUCLIDES ™ plant consists of 14 arrays, 84 meters long, each with 140 linear parabolic mirrors and 138 receiving modules series connected. The collectors are parabolic troughs with one axis tracking, oriented North/South and parallel to ground. The receiving modules were manufactured by BP Solar Ltd., and the rest of the sub-systems were developed by IES in a previous JOULE IV project. ITER was responsible of the mirror and structure set-up, overall installation, site preparation, inverter fabrication and grid connection.

The objective of this paper is to describe the installation of the whole plant, to present the initial performance and to asses the cost per W_{peak} of this technology. The cost analysis promises that 3.84 ECU/W, all included for grid connection, is achievable at 10 MW/year production.

Keywords: Concentrator –1: Large Grid-connected PV systems –2: Parabolic Trough –3

1. INTRODUCTION AND OBJETIVES

This plant, based on the technology of the EUCLIDES™ concentrator, developed in the JOULE programme, was proposed to and subsidised by the THERMIE programme in 1996. The nominal power of the concentrator plant is 480 kW_p, using parabolic troughs and is shared in 14 arrays, each 84 m. long. (Fig. 1, 2 and 3.). The goal of this project was: (a) to demonstrate this technology in a real size plant; (b) to identify the most adequate sub-contractors for developing the tools and manufacturing the components of this technology; (c) to learn with accuracy the costs of the components in order to probe the cost reduction potential of the technology; (d) to asses the components and plant performance. The EUCLIDES™ components are: the concentration cells encapsulated into receiving modules, the passive heat sink, one axis tracking structure, transformer-less inverters and the mirrors.

The energy produced will be sold to the local utility at 0.216 EURO/kW.h, according to the current Spanish regulation.

At present, the project is in the phase of commissioning, and we hope to start the monitoring and continuous production in the coming months.

2. SHORT DESCRIPTION OF THE PLANT AND ITS SUB-SYSTEMS

The RTD JOULE project named EUCLIDES™ led to the development of a full technology of PV concentration in 1994-95. A prototype 24 meters long was manufactured, and its performance was tested since September 1995 in Madrid. The efficiency obtained was 14.42 % (at 800 W/m^2 and 25ºC) and 10.95 % at yearly averaged operating conditions in Madrid [1-4].

Figure 1: Aerial view of the EUCLIDES Plant installed in the grounds of ITER in Tenerife (Canary Islands, Spain)

Figure 2: View of an array, with the tracking control box

Figure 3. A partial view of the PV field during initial operation set-up.

Figure 4: The seven TEIDE inverters for the fourteen arrays.

Based on this technology, the Instituto Tecnológico y de Energías Renovables (Tenerife, Spain), the Instituto de Energía Solar (Madrid, Spain) and BP Solar Ltd. (Sunbury on Thames, UK) have carried out the project of the world largest PV concentration grid-connected power plant: the EUCLIDES-THERMIE plant. It has been installed in the south of Tenerife (Canary Islands) in the grounds of ITER. This Institute co-ordinates the project and will own and monitor the plant. BP SOLAR acts in this project as supplier of the whole plant and is recipient of the EUCLIDES™ technology.

Figure 5: Close view of the wheel and the linear tracking mechanism.

The arrays, with 250 m^2 collector aperture, are North/South oriented and close to the ground. The geometric concentration ratio is X38.2, 1.2 times the one in the prototype (However only 9% of light collection increase can be expected by theoretical reasons). The mirror technology is based on metallic reflective sheets shaped with ribs to the optimum parabolic profile. Three different materials have been tested to be used as reflective material. The fully encapsulated receiving modules are made of 10 concentration LGBG BP Solar cells, also series connected. The modules are cooled with a passive heat sink.. Every two contiguous arrays are connected, in parallel, to one inverter sized 68 KVA. The output voltage at standard operating conditions is 750 Volts. The inverter, without intermediate transformer, was designed and manufactured by ITER [5].

3. OVERVIEW OF THE INSTALATION PROCESS AND LEASONS LEARN

3.1. The structure design was improved, simplified, with respect to that of the prototype and checked to withstands normal and extreme wind loads. [6]. It was built by JUPASA (Toledo, Spain) that arranged the elements to be shipped from the port of Valencia to Santa Cruz de Tenerife. Once arrived to the site all the beam elements were assembled, some steel reinforcements welded. Then sandblasted and painted. Then the beams were mounted on the previously installed central table were is located the driving mechanism.(Fig.5)

The operation took as much as 4 days to install the first but the 2 last arrays last were erected in 1 day each. All the work was carried out just with a truck provided with a 6 Tons crane. In spite of the weight and size of the steel array tracking structure (160Kg/m), the alignment of the axis, as measured at the central table, is better than 0.0003 radians, that is sufficient for correct operation and it was achieved using simple optical devices. The maximum bow was 12 cm. as predicted by the theory in value and location.

The effect of stationary wind (up to 30 Km/h) on the power output has not been observed, probably because other mismatch effects are currently larger than the wind one. The driving mechanism, a new version developed for this project, converts a powerful (200 kNewton) but smooth linear movement into a circular one by means of a pair of automatically equilibrated steel cables. Although the array structure of the prototype EUCLIDES (Madrid) must be deployed horizontally, the current design permits to tilt the axis up to 12 degrees. The tilt of the arrays in

Tenerife progress from 0.5 degrees at the most eastern to 5.5 degrees at the most western.

3.2 *The tracking control system***,** fabricated by INSPIRA, adopting IES designed tracking strategies [7], was operative immediately after its connection, because it was previously checked at the Madrid prototype. The control unit has been operating in a continuous way in the last 8 months with a maximum pointing fixed to 0.2 degrees, but can be reduced to 0.05º, if required. The tracking control unit generates along all the system life a table of small angle values that corrects the theoretical (astronomical) position to a closer one providing more output power. From those small correcting angle values (shown in Fig 6) the errors in the calibration constants or a deviation of the array axis with respect to the N/S line can be known.

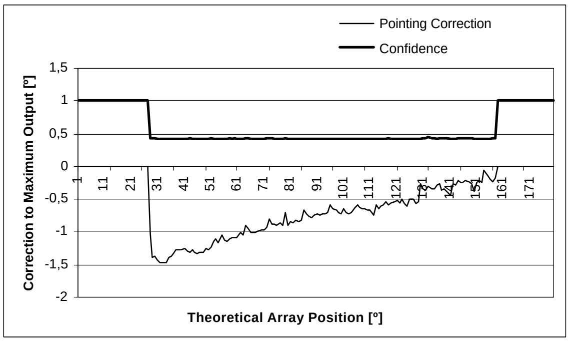

Fig 6 : Correction to calculated tracking angles to get maximum power output.

3.3. The Receiving Module

A second generation of receiving modules were developed for the EUCLIDES plant based on the experience of the Madrid Prototype modules that led 17 % efficiency at Standard Test Conditions. The new cells are larger, 11, 6 cm long and only ten were included in each module. The current capability of the by-pass diode was adapted to the larger cells and mirrors. Before the fabrication was initiated the cells and module interconnects were modified to decrease the series resistance from 13 to 10 mohm, and the sheet thermal resistance was reduced to 3-4 ºC.cm^2/W between the cell and aluminium substrate.

There was also some time before the fabrication to check the quality of 10 modules for this new application, testing the module performance before and after several stressing processes. Humidity and temperature cycling, hi-pot at 2600V, normal operation and hot spot conditions under natural concentrated light during 800 hours. The fabrication was initiated recording the 1 sun I-V curve , the I_{sc} at 27,5 suns with flash lamps, and predicting the performance at concentration with an I-V curve recorded at dark conditions [8]. The rejection limit was fixed at 215.64 W at STC. Fig 7 shows the distribution of the fabricated modules. The connectors of the module were greatly improved respect to the first design, but still more development is required on this subject, not only for reliability but for easy field receiving mounting & dismounting.

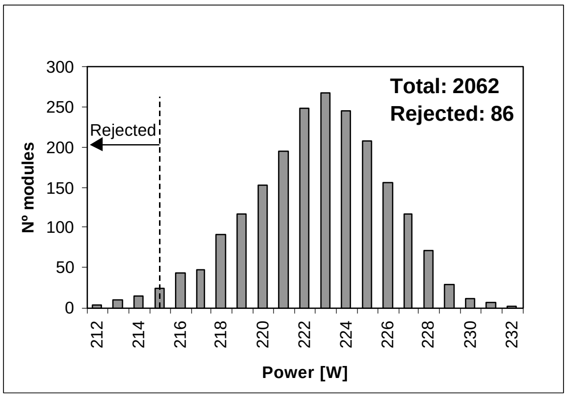

Figure 7: Power histogram of receiving modules at STC.

The modules were glued to heat sinks with a "thermal" acrylic adhesive that cures at room temperature. The module heat sink assembly were installed on the array and connected before the mirrors were. To avoid high voltage risks at the connection the modules were joined first in groups of 8 (about 40 volts)

3.4 The Mirrors

The shaping of the mirrors at the site longs several months because the cure time required for adhesive was 40 minutes at high temperature. Now, fast room temperature adhesives have been tested reducing the time by 5 times.The yield of this process was very high (99,5%), demonstrating that it can be done at the site, by not specially skilled personnel.

The reflective materials used in this plant are not optimised, because they were not previously tested for long outdoor exposure. The assumption of that risk was forced by the unavailability of the film 3M ECP305, the one tested during 2 years in Madrid and previously selected for the project. The mirrors cannot be installed as they were shaped, The storage caused some damage at the sealing film at the mirror edges. If the array was already tracking, the mirrors were aligned to focus during the mounting process. The trimming process was visual, locating the spot line on the receiver. Later, we verified that such visual method yield Isc values close to the maximum available current.

The installation of the mirrors on the arrays was a fast and simple task that consumed only 6 ManHours

The cleaning of the mirrors and receivers is a task that can be carried out in a simple way with workers located on the ground floor, thanks to the EUCLIDES structure concept.

3.5. The inverters

The solution adopted for the DC/AC conversion is not the most conventional for power plants, one big inverter, but for the sake of modularity, every EUCLIDES™ concentrator unit were delivered provided with its own inverter, Although such an approach guarantees the maximum modularity of the system and also gives very good reliability (the failure of an inverter affects only one unit), economical considerations and marketing advised that two arrays should share the same inverter. Modularity is then kept at the level of 68kWp. Therefore, this EUCLIDES™ plant has seven modular inverters 68 kWp, for every two arrays (Fig.4). The seven inverters are connected in parallel to the primary of the medium voltage transformer (380V/20KV). Avoiding the intermediate transformer saves around 4% of the overall energy of the plant. In the following Table I and Fig 8 the technical specifications of the inverters are shown.

Table I. Technical characteristics of the TEIDE inverter

Manufacturer	ITER
Rating	68.5 kWp x 7
Input (min)	600 V
Output	380 V
Eff. at rated power	97%
Eff. at 10% of rated power	95%
Total harmonic distortion	<1%

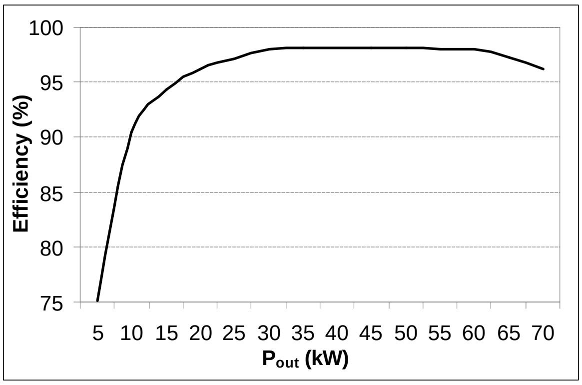

Figure 8: Efficiency curve of the inverters

Every inverter has the possibility to regulate its total, active and reactive power output as well as some other operating parameters, which can be either controlled externally, over the field bus, or by an internal programmable strategy based on MPP tracking algorithms.

3.6. Central Control Weather and Monitoring Station

It stands nearby to the plant and is used to monitor external magnitudes as outside temperature, wind speed and direction, direct solar radiation, global radiation, modules temperature, etc. The electrical parameters of the plant are also recorded at the inverters input and output, located in the control building with the 380V/20kV grid transformers (Fig. 9).

Fig. 9: Control building and visitors centre with the meteorological station at the top.

The magnitudes will be recorded and distributed following the recommendations of ISPRA (CODIGO DEL PAPEL), but some of them are specifically defined for this project because the lack of standards for concentration PV systems.

4. COMPONENTS AND PLANT PERFORMANCE

As the plant is still in commissioning,, there are not yet recorded continuous reliable operational data but several experiences carried out can inform about the initial performance and the trimming still required to optimise the output. Up to date, we can report that:

The structure withstood winds up to 90 Km/h twice last year without any sensible damage (just 20 mirrors were partially unglued from its ribs). The reliability of the overall tracking system has been demonstrated after 6 moths of continuous operation. The windy and salty conditions at the site reduce the optical efficiency 20 % per week, due to deposits on the mirrors and receivers, much if compared with the 2-3 % in Madrid.

The measured optical efficiencies are 85 % for one mirror, and 77 %, too low, for an array. The early array IV curves show a mismatch effect along the array that seems connected with the low optical efficiency. The problem is being investigated (Fig. 10).

Several arrays have been consecutively connected to the inverters allowing injection of power to the grid up to 17.2 kW at 850 W/cm2. This figure is justified by the low optical efficiency and a higher than expected operation cell temperature. After a few days under operation, several modules lost insulation, grounding the active cell line of its array. It prevented the power injection of the array to the grid and activated the safety alarm. This kind of failure has later occurred to 3 % of the modules (i.e. 58 receivers) but spread in all the arrays. This failure is quite surprising because the module insulation was tested, as said above, at 2600V. and the previous development laboratory tests reach more than 4000 V. Unhappily the identification and the substitution of the grounded modules is a difficult and very time consuming task.. BP Solarex will manufacture additional modules to substitute those presenting leakage in the plant once the failure reasons are identified. Then the the arrays will inject power again across the 7 inverters already installed.

During the off-grid periods we measured several figures of merit of the plant and the effect of defects and trimmings. The parameters investigated were: the electrical characteristics of arrays, the optical performance of the overall system, the thermal parameters in load, the optical aperture, the methods for mirror alignment, the mirror cleaning requirements, the possible components degradation, etc.

The effects of the array optics on the power output and Isc of the EUCLIDES system is presented in detail in a paper in this Conference to which you are addressed [9].

The whole IV curve of an array has been measured with a transient load developed for the EUCLIDES array voltage, close to 1000 V. The curves obtained in one array is the one shown in Fig 10 The curve shows a significant tilt (false shunt resistance) due mainly to optical mismatch along the array caused by misalignment of the mirrors, excessive gap between them, dispersion of mirror quality and of module performance. (However the modules were selected to be installed in series with very low electrical mismatch, within +/- 1%).

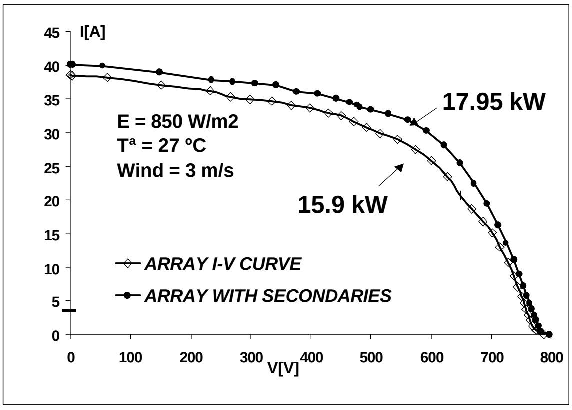

Figure 10: IV curve of an array with 138 modules in series.

To reduce the loses due to a the possible misalignment we installed in one array a secondary concentrator to increase the power output.(Fig. 11) The second IV curve in Fig. 10 demonstrated an increase in power output of 11 %, This amount was due to a major collection of light, valued as 3 % in tests of individual modules, and the rest, about 8 % must be attributed to mirror misalignment. The rest up to 21 % will be caused by mirror discontinuities or errors running parallel to the array axis, and not affected by the secondary. The current overall efficiency is 8.4%.

The loses can be understood with Fig 12. where the array and module currents versus the sun misalignment are plotted. The figure shows that the angle of aperture of the array regarding the short circuit current is much wider than the aperture regarding the maximum power output (point B) and also that the available Isc for the maximum power is only 83 % the maximum Isc of the array. This effect due to small misalignements of mirrors between themselves, requires a tracking accuracy of +/- 0.05, while the system is now operating at +/-0,2 degrees.

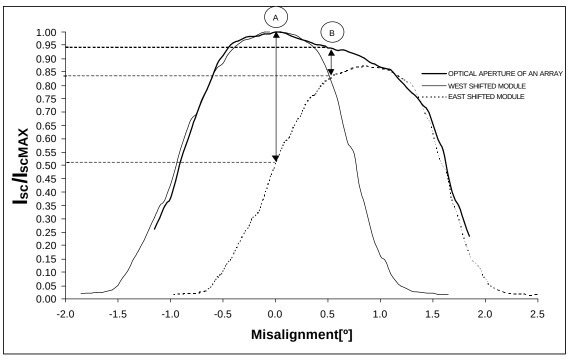

Figure 12: Angular aperture of an array in comparison module with the aperture of the most shifted modules.

This demonstration plant allows for the first time to study the real problems associated to pre-industrial concentrators, because all previous works were carried out at laboratory or prototype level.

Figure 11: Array equipped with V-secondary concentrators

5.COST AND PERSPECTIVES

One of the objectives of the demonstration project is to know realistically the cost of the plant and the impact of each components using the EUCLIDES technology, once everything has been terminated and all the necessary but non scheduled works have been carried out. But as this EUCLIDES plant is the first erected, one of demonstration, the total project cost is not the required figure, because there are included new designs, R&D, engineering, tooling and managing activities that will not be present in successive plants. Discounting the expenses of those items it was found that the Toledo demonstration plat cost was 7.66 EURO/W_p (or 7.34 \$/W_p) and that this EUCLIDES-Tenerife plant has cost 5.14 EURO/Wp (or 4.93 \$/Wp), including in both cases the inverter and the grid connection. We guess that the cost reduction is significant, taking into account that in Toledo the know how of flat module installation was already acquired, but in EUCLIDES everything was new. In consequence the objective of 3,84 EURO/Wp (or 4.03 \$/Wp) for a production of 10 Mw/year seems very possible. In Table II we present the cost of every subsystem and other associated costs and forecast.

6. CONCLUSIONS

The EUCLIDES array concept, as one close to ground, is advantageous regarding the wind loads, the mounting requirements, the cleaning and the maintenance. Also it has been proved to be a singular solution because the BP Solar concentrator cells are the only competitive today. The industrialisation of the components has required very small investments in tooling (in the range of 800000 EURO), far from the usual investments on other promising cost reduction PV systems (like thin films). On site manufacturing of structure, mirror shaping and receiver assembly has been demonstrated.

Regarding the dissemination of this technology is advisable to fix standard rules for qualification, specification and rating of PV concentrators.

Regarding the initial problems found in some modules operation at reduced voltage will be checked in the next months. Investigation of the causes of optical mismatch must be issued. The use of secondaries as already tested in one array on alternative series/parallel connections inside the modules are immediate alternatives. The continuous

Table II: Cost of the EUCLIDES-THERMIE power plant (discounted tooling, engineering, and management cost)

Sub system	Cost (EURO)	Cost Wpeak (EURO)	Cost Wpeak ($)	Projection (EURO)
STRUCTURE & TRACKING	703845	1,466	1,404	1,10
MIRRORS	252425	0,526	0,504	0,45
HEAT SINKS	159395	0,332	0,318	0,33
RECEIVING MODULES	390658	0,814	0,779	0,81
Total Sub-Systems	**1506323**	**3,138**	**3,005**	**2,69**
MATERIALS & SUBCONTRACTORS	405310	0,844	0,809	0,80
TRANSPORTATION	93145	0,194	0,186	0,15
ON SITE MANUF & INSTALLATION	128708	0,268	0,257	0,20
TOTAL PLANT	**2133486**	**4,445**	**4,256**	**3,84**

monitoring along two years will provide the required information to reach maturity of this technology. According to the project experience and the manufacturing engineers, we expect that the most significant cost reductions will come from the structure-tracking and also from the operating efficiency. The cost reduction of the EUCLIDES technology has been demonstrated in comparison with previous flat panel grid connected plants. Analysis of each component cost shows that power plants in the range of 3.5 to 4.0 EURO/Wp at 10 MW/year production are achievable in short term with this technology.

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The project has been subsided in the framework of the JOULE-THERMIE IV Programme.