480 kWpeak EUCLIDES^{TM} Concentrator Power Plant Using Parabolic Troughs

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ABSTRACT: Based on the technology of the EUCLIDES Concentrator, developed in the JOULE programme, a demonstration plant was proposed to and subsidised by the JOULE-THERMIE Programme in 1996. The objective was to identify the most adequate sub-contractors for developing the tooling and manufacturing the components of this new technology to probe its industrial feasibility and cost reducing potential. The EUCLIDES components are all original developments for this parabolic trough concentrator: cells encapsulated into receiving modules, passive heat sinks, metallic on site shaped mirrors, one unique axis tracking structure for 250 sq. meters and transformer-less inverter. An accurate model of all the components allows to calculate the energy to be produced at any site. According with the actual cost of the system, the energy produced in Granadilla, at the SE of Tenerife Island, will cost 0.136 $/kW.h, it is, 58 % of the cost if produced by a flat panel system of the same size on the same site. The plant is now being deployed and will be finish and grid connected by October 1998.
Keywords: Concentrator, Parabolic Trough, PV Power Plant, One axis tracking, Parabolic mirrors, Grid connected

1. INTRODUCTION

The Project EUCLIDES^{TM} , one subsidised by the European Union in the frame work of the JOULE Programme, demonstrated since September 1995, the feasibility to obtain high efficiencies casting the light collected by reflective parabolic troughs on low cost BP Solar Laser Groove Buried Grid (LGBG) concentrator solar cells. The efficiencies obtained on the prototype, 24 meters long, Fig. 1, at 800 W/m^2 , 25 ºC and in operation conditions in Madrid were 14.6% and 9.6% respectively. (References 1,2,3).

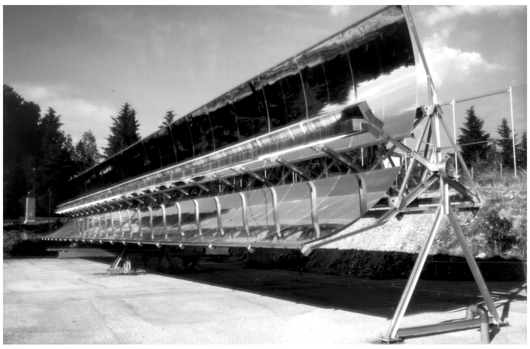
Based on this proved technology, the E.U. has subsidised the world larger PV concentrator grid connected power plant, “The EUCLIDES-THERMIE Plant” now being installed in Tenerife (Canary Islands) close to the 22 MW windmill park of ITER (Institute of Technology and Renewable Energies of Canaries). ITER co-ordinates the project, installs the whole system and will monitor the plant. The other partners are BP Solar Ltd. in U.K. and the IES-UPM. BP Solar plays a double role in this project, as supplier and as recipient of the EUCLIDES^{TM} technology, gaining on field experience in this kind of systems.

This project is not a classical demonstration one, in the sense that all the components were not yet industrialised nor commercialised before this plant is deployed.

The suppliers of the components had already shipped the 80% of the goods to Tenerife where they are currently assembled. The plant will be operative by October 1998, six months later that scheduled. The overall cost of the project is 525 millions of pesetas, including managing, tooling development, acceptance tests, components qualification, monitoring and documentation.

The knowledge of costs gained along this project allows to fix an objective of 3.3 US$/Wp in the long term for a 15 MWp/year production level.

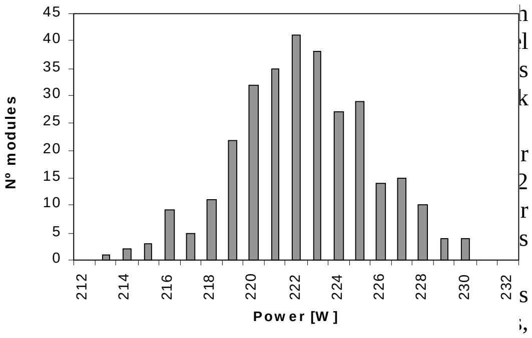
Figure 1: The EUCLIDES prototype, 24 m long,



installed in Madrid since September 1995.

2. GENERAL DESCRIPTION OF THE PLANT

The plant sized 480 kWpeak consists of 14



series connected. The modules are cooled passively with a lightweight heat sink that is an industrialised version of the one already used in the prototype.

Every two contiguous arrays are connected, in parallel, to one inverter sized 60 KVA. The output voltage at standard operating conditions (SOC: 800 W/m^2, 20ºC ambient temperature, 2 m/s wind) is 750 Volts. The inverter, without intermediate transformer, was designed and built by ITER. It provides 220/380 Volts output to be directly injected to the grid.

More information about the fundamentals of this technology can be found in the above mentioned references.

3. THE COMPONENTS OF THE PLANT: DIFFERENCES AND IMPROVEMENTS RESPECT TO THE PROTOTYPE ONES.

3.1 The receiving modules

The modules are sized around 1.20 meters long, like the prototype ones, but now the cells are 1,2 times larger and only 10 are included on it. This new cell size provides several advantages: *a)* saving material and cell fabrication costs, *b)* decreasing the optical mismatch loses between mirror and receiver, and *c)* reducing the overheating of any reverse biased cell because only 10 cells are now by-passed by a diode, instead of the 12 cells in the early module.

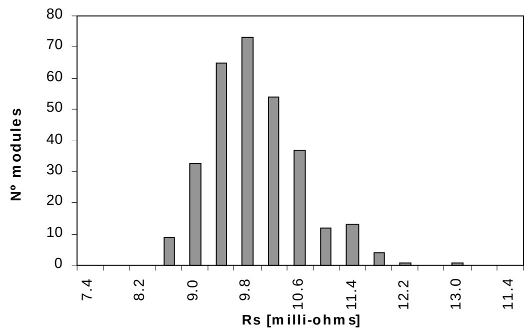
If larger the cell area then lower the absolute value of the series resistance but the percentage of loses is the same. Then to reduce the series resistance of the modules, for a given cell technology, the only way was to reduce the series resistance of the interconnection tabs in a percentage larger than the area increase. This has been done in the new modules were the tab contribution is 1.7 mohm, instead of 4.8 mohm in the old ones. Then the 13.2 mohm with the old tabs, becomes only 10.0 mohm with the new ones at the operation current level. The effect in the total efficiency at STC, 25 ºC is to pass from 16.9 % to 17.4 %.

Happily, a further decrease in Rs is still possible modifying several cell parameters, as is done in the project SICOCELLS (JOULE Programme).Figures 2 and 3 show the histograms of the series resistance and the power output for the first 302 modules produced. Both have been measured at the concentration level on the production line with the equipment TRANSCORDER-500 (see paper VC4.23 in this conference).

Figure 2: Histogram of the power output of 302 modules at STC, as measured with the TRANSCORDER-500.

Figure 3: Histogram of the series resistance of 302 modules as measured with TRANSCORDER-500

Another dramatic improvement achieved in the new receiving modules is the reduction of the thermal drop between the cell an the aluminium substratum. The measured thermal resistance has passed from 12.3 ºC.cm2/W to 2.8 ºC.cm2/W.It means that at standard testing irradiance (i.e. 800 W/m2 beam irradiance or 2.754 W/cm2 on the cell) the thermal drop is reduced 26ºC, affecting significantly the efficiency. Table 1 shows the



efficiency increases caused by each improvement and both combined. Fig 4 shows a close up of the new and the old module. The tab region is now shielded to avoid local overheating if the concentrated spot focus on that less heat sinking area.

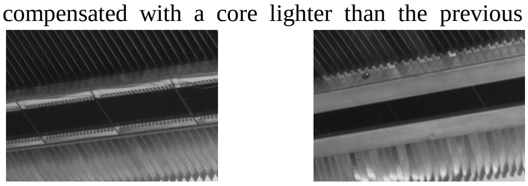
Table 1. Effects of the improvements on the receiving modules.

Module technology	Rs (mhoms)	Effic.at 25ºC (%)	Cell temp at SOC(ºC)	Effic. at SOC (%)
Tenerife	10.0	17.4	63.9	15.1
Prototype	13.2	16.9	90.0	13.2

Figure 4: The old and the new module under concentrated light.

3.2. The heat sink.

The original “non-extruded thin fin” heat sink design , providing passive cooling, has not been modified. The company Alusuisse has been contracted to manufacture, in its factory at Singen, Germany; the 2000 elements required for this project. To ease the manufacture, the fins are thicker than the optimum, but this excess of material has been compensated with a core lighter than the previous



one. The new fin thickness will allow to increase, still efficiently, the length of the fins for higher concentrations for the same core tooling..

Once the receiving module is glued on the heat sink , the assembly must be located at the focus of the parabolic mirror. To easy this “field work” two especial and thick fins, permits to hang the assembly till its final fixing with nuts:

3.3. The mirrors.

Like the prototype, the collectors are linear parabolic mirrors mounted in a continuous way along the 84 meters of the array in order to avoid any shadow in the series connected cells. The technology consists of reflective films glued on aluminium plates that later are shaped to a parabola profile with two ribs.

The mirror aperture for the Tenerife plant is 1.2 times larger than the one used in the prototype. Now the mirror will cast all the energy in a strip 26 mm wide (the active cell width is 40 mm.). Regarding the cost, the increase of the mirror area do not affect substantially the cost of this component but will increase the power output about 1.16 times. (the sub-linearity is caused by the major temperature of the cell for a given heat sink). The EUCLIDES™ mirror technology allows shaping on the site by not specially skilled workers. Such quality is of major significance because the room occupied by terminated mirrors and the extreme care that would be required in transportation

The field experience of the prototype along three years confirmed that the acrylic silvered film ECP305 from 3M was the best reflective surface for our mirror technology. But when we ordered the 5000 m2 required for the plant our order was not accepted. It seemed that they have lost that technology because the samples sent to justify the order rejection were really not acceptable.

We were then forced to do a fast research on alternative materials that we had programmed to initiate after the EUCLIDES-THERMIE plant was terminated. The alternative films must complaint with the following conditions: Reflectivity, weather-resistant, low cost, availability, delivery time and technology compatibility.

Up to 25 different films or combination of films have been experienced, checking surface dispersion, reflectivity, salty, wet and variable temperature cycling, ultraviolet resistance, fabrication compatibility and testing of terminated mirrors. All this research work, done at the IES with the help of BP Solar España, has caused an unavoidable delay of the plant installation. Much of the time has been lost asking and waiting for samples to the manufactures and cycling them in the test chambers. The partners of the project thanks to CIEMAT, the well known Spanish research centre, for the help received along all this work.

The results recommended to use in Tenerife three types of reflective films shared in the following way:

a) 4 arrays with polished aluminium film 0.5mm thick, glued on an aluminium substratum 1.5 mm thick.

b) 9 arrays with a silvered plastic film covered with a transparent weather-resistant acrylic film that lay also on an aluminium substratum 1.5 mm thick.

c) 1 array with a factory-made sandwich of a weather-resistant silvered plastic film on 1.5 thick aluminium substratum.

The options *a*) and *b)* requires the lamination of all the layers as intermediate process to obtain the reflector working sheet , but in option *c)* the factory serves the reflector sheet terminated.

Options *b*) and *c)* show practically the same reflectivity as the ECP305 film but the reflectivity of option *a)* is only 82%. Due to the associated decrease of the cells temperature the annual energy produced is reduced only 7%, less than the reflectivity does. Affecting only to 4 arrays the percentage of loses for the total plant will be 2%. This experiment will inform about the claimed superior outdoor lifetime of aluminium and its better average energy collection. The lower reflectivity of aluminium could be compensated, in future plants, if necessary, with a larger mirror.

The spot of the new mirror is 26 mm wide, larger than the old one, but in the same relation than the mirror size.

3.4. The Tracking Structure. The first long array and the acceptance tests.

The size of the array, 84 meters long, 250 m^2 of aperture, have been optimised to share the structure and the tracking system costs. The requirements of accuracy, stiffness and cost over so large aperture are object of a monographic paper presented at this conference (see VB6.16). Figure 5 shows the structure of the first array built. This unit was used to perform all mechanical acceptance and qualification tests, because the nominal full length was never previously experienced.

Figure 5: The structure of the first array built 84 m long, located at Yuncos (La Mancha).

The design of the prototype array was revised to reduce components, to simplify the fabrication, to withstand the larger forces on the system and to easy the transportation and field installation. The acceptance test of the first array were initiated on September 1997, before the mass production was approved. To simulate the forces and the moment induced by the mirrors, the receivers and the wind, the system was loaded with sand bags in a distributed way as shown in Fig5. The performance of the system respect to "flat" loads, those affecting the bow of the structure axis were within the predicted limits (13 cm along 42 m) but the torsion loads caused twice the deformation allowed to operate at the 95% of the maximum output at winds 40Km/h. A simple and straightforward solution was adopted to increase the stiffness to torsion.

Also the structure was analysed in simulators to know its ability to withstand winds up to 150 Km/h without permanent damage. It was found that few reinforcements could provide the desired performance at limits. The counterpart of these interesting experiences was that the tests and the adoption of solutions long for three months due to the continuous raining in central Spain, becoming one source of delay for the project.

Now the operation at 40 km/hour winds still casts 95 % of the available concentrated light beam on the cell. These figures emphasise the extreme rigidity achieved with a still lightweight steel structure (0.5 Kg. of steel/Wpeak). However the modifications required in this first experience avoided to reach the objective of cost reduction targeted for this case. Fig 6 and 7 shows details of the first structures in the Tenerife Plant.

Figure 6: A view of the site at ITER. Central basements for 14 arrays. Beginning the deployment of the first array. (June 25th, 1998)

Figure 7: Carriyng the first driving mechanisms form ITER workshop to the field.

3.5. The tracking control unit.

One tracking control unit is assigned to each array. It operates based on sun astronomy equations plus a self-learning strategy that optimises the sun pointing looking at the maximum instantaneous incoming power.(Ref 4).The accuracy of the tracking is set to +/-0.2 degrees to reduce the frequency of start-stop cycles. The system is now commercialised by the Spanish company Inspira that has also industrialised the previous system developed by IES-UPM. Fig 8

Figure 8: The tracking control box, (by INSPIRA).

3.6 The dc grid and the inverters.

Each array carries 140 mirrors and 138 modules, each with 10 cells in series. The short-circuit current of the modules of each array is within +/- 1% tolerance. The 138 modules are series connected in each array. They provide a minimum acceptable voltage over 700 volts at the worst conditions, in order to use a "true" three phase inverter without intermediate transformer. The interconnection length between modules is minimised because the module terminals are contiguous along the 84 meters. The electrical insulation of all the modules is checked at 1500 V and rejected if not pass. The module interconnection is assured with double water-proof shrinkable connectors.

The solution adopted in this plant for the DC/AC conversion is not conventional. First of all, there is not one, unique big inverter specially designed for this plant, but seven modular inverters 60 kVA peak, for every two arrays. In this way the modularity of the EUCLIDES^{TM} system is maintained and the advantages of large production (> 250 units per year, and less engineering) can be achieved. The second improvement, or novelty, is the connection of all inverters in parallel on the primary (low voltage side) of the transformer (380V/20KV) used to connect the whole plant to the grid. Avoiding the intermediate transformer saves around 4% of the overall energy of the plant. More details about the inverter TEIDE developed at ITER and the dc/ac system are presented in two papers at this Conference.(papers VA5.12 and VA5.13)

Table 2: Parameters to model the operation and production of the EUCLIDES Array

Cells and modules	
Eg	1.092 eV
m	1
Rs module	0.014 ohms
Rs wires + tabs	0.0027 ohms
Ao, cell area	46,4 cm^2
Iscmax (1 sun)	1.53 A
Voc (1 sun)	0.600 V.
Modules	138
Cells/module	10
Nº cells in series	1380
Concentrator Paratemeters	
Mirror area	1.7962 m^2
Opt. Efficiency	0.90
Geom concentr. Ail/Ao	38.2
Missmatch	0.95
Thermal Parameters	
Rth Cell-tray	2.8 $^oC.cm^2/W$
Rth Heat Sink ideal (no wind)	18.5 $^oC.cm^2/W$
Rth tray/heat sink	1,0 $^oC.cm^2/W$

4. THE PERFORMANCE OF THE EUCLIDES-THERMIE POWER PLANT. MODELLING THE OPERATION FOR ANY SITE.

The operation of the prototype for three years has yield much information about the optical efficiency, wind effects, tracking errors ,etc. affecting the operational characteristic of the EUCLIDES array. On the other hand the thermal characteristics of the heat sink and the module are currently well known from indoor experimental data. Also the formulas to correct the IV curve versus temperature and concentration are fitted with an experimentally obtained value (Eg=1.092 eV) for the silicon band-gap that accounts for the band shrinkage at the cell emitter. The values of the ideallyty factor, *m*, and the series resistance are now accurately known and, finally, the IV curves of all the modules at operating conditions are recorded at the production line. Also the effects of the illumination non-uniformity on the cells have been modelled (Ref. 5) and verified.

All this information permits to model very accurately the performance of the array under any climatic condition. Table 2 shows the values of the parameters of the model.

Based on the model we can calculate very accurately the energy that will be produced by the system in Granadilla, Tenerife. As an example, we show in Table 3 the efficiencies and the energy produced by an array in the following cases: a) Prototype mirror with prototype modules; b) the Tenerife mirror (20% larger) with the old module, and c) the large mirror with the new module. The improvements in the energy produced are significant: 34 % from prototype to current technology, where 16% is due to module improvements.

Table 3: Efficiencies at operation and energy produced by an EUCLIDES array with different types of modules and mirrors in Granadilla.

Month	**Efficiency (%)**			**Energy produced (kW.h)**		
	A	**B**	**C**	**A**	**B**	**C**
Jan	11.7	120	13.4	2274	2641	3014
Feb	11.9	123	13.5	2600	3024	3424
Mar	11.2	11.5	13.0	3687	4269	4973
Apr	11.0	11.4	12.9	4182	4837	5670
May	11.0	11.4	12.9	5171	5981	7005
Jun	11.0	11.4	12.9	5137	5943	6957
Jul	10.9	11.3	12.8	5844	6763	7893
Aug	10.8	11.1	12.6	5232	6049	7093
Sep	11.1	11.5	12.9	4146	4804	5561
Oct	11.2	11.5	12.9	3297	3819	4420
Nov	11.8	12.2	13.4	2244	2609	2948
Dec	12.4	12.7	13.8	2012	2348	2613
T year	-	-	-	**45828**	**53086**	**61572**
Relative increase (%)				*100.0*	*115.8*	*134.4*

A: Prototype module and mirror
B: Prototype module under Tenerife mirror (1,2 x larger)
C: Tenerife module and mirror.

The energy produced per each kWpeak of rated power are practically equal in Granadilla for the EUCLIDES concentrator and for a flat panel tilted to latitude located in the same site. These are 1709kW.h/kWp for the concentrator and 1773 kW.h/kWp for the flat panel.

5. COSTS OF THE EUCLIDES TECHNOLOGY.

It is easy to account for the cost of the plant when all the invoices are on the table. However the installation is not yet finish but an approximate valorisation of the cost can now be done.

As it has been usual in our previous presentations we shall compare the cost of the EUCLIDES technology with the flat panel one in the case of a plant of the same magnitude and also grid connected, as is the TOLEDO PV plant also subsidised by the THERMIE program. If we take into account the energy produced by each kind of system then the energy cost can be easily compared. The Table 4 shows the cost information.

Table 4: Total cost for conventional flat panel and EUCLIDES Plants. (for EUCLIDES the figures are accurate forecast)

ITEMS	TOLEDO PV	EUCLIDES 15 MW/year
Modules	5.40	0.80
Structure, tracking & installation	0.66	1.70
Mirrors	-	0.56
Heat sink	-	0.32
Field preparation & wiring		0.27
Inverter and transformer	0.86	0.27
Others & site works (mounting)	0.11	0.09
TOTAL COST	7.34	4.03

Taking into account the energy produced for each system , and considering a constant return ratio of 5.6 % the cost of the energy is shown in Table 5.

Table 5: Cost of the Energy produced by flat panels and EUCLIDES at the site plant, in Granadilla, Tenerife. (rate of return of capital 5,6 %)

ITEMS	TOLEDO PV	EUCLIDES 15 MW/year
Energy prod. per kWp	1773	1709
Energy cost ($/kW.h)	0.232	0.132

Costs are reaching what was presented in the last PVSEC (Barcelona)(Ref. 2)

6. CONCLUSIONS.

By the time of writing this paper the status of the plant permits to know perfectly the cost of the components and their specifications because more than 70 % are already in the site. The costs predicted in .Barcelona are maintained at production level. as predicted. The modelling of the systems permits to predict the expected performance. The energy production has increased 34% respect to prototype, where 18 % is due to the increase of the mirror size).

Has been demonstrated the acceptance test of concentrator cells and modules in concentration at the factory. Three new available mirror technologies fulfil the system requirements. The shaping process of the mirrors in the site has been demonstrated. Painting and assembling the structure on the site is demonstrated, with simple tooling. The local contribution to total EUCLIDES cost is close to 20 %. The possibility to built light but stiff long structures up to 84 m (12 m longer than projected) is demonstrated. The concept of modular inverter yields still lower costs than expected. The EUCLIDES energy costs 58 % of the flat panel one (i.e 0.136 $/kW.h vs. 0.232 $/kW.h in Granadilla)

Still some research is necessary to reduce costs. The hard environmental conditions of Tenerife are excellent to inform fast about any possible failure. The size of the plant was really the minimum size to arouse some interest from the sub-contractors. Also suggested The difficulties of mass production have been envisaged. EUCLIDES becomes an available technology requiring 35 times less silicon than conventional panels. This demonstration plant will be the main basis of confidence for users and manufacturers on the concentrator technology in the short term.

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