**PETAL: A RESEARCH PATHWAY TO FOSSIL-COMPETITIVE SOLAR ELECTRICITY**

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**ABSTRACT**

We outline the economic arguments in favor of using large parabolic dishes for CPV. We then discuss methods that have been employed to quantify the optical and tracking properties of PETAL, a 400 m² parabolic dish facility located at Sede Boqer in the Negev desert. Attention is drawn to the problem of light homogenization at the focal plane, and a method is discussed for achieving adequate homogeneity for CPV purposes.

**INTRODUCTION**

PETAL (an acronym for Photon Energy Transformation & Astrophysics Laboratory) is a 400 m² parabolic dish with a focal length close to 13 m, and variable concentration up to approximately 10,000X. It was designed, as its name suggests, to be a multi-purpose research tool. PETAL’s paraboloidal surface is constructed from 216 mirror panels with triangular perimeters. Because of its overall hexagonal symmetry there are only 36 different mirror panels, each having 6 replications [Fig. 1]. Each of the panels can be manually aligned so as to vary the achievable concentration. For the purpose of the present discussion we shall consider a situation in which the 400 m² of incident solar irradiance is redistributed over a 1 m² area of CPV cells – i.e. a situation in which PETAL is operated at 400X concentration.

This presentation will be structured in two parts. In Part 1, it will be argued that the use of very large parabolic dishes, of the size of PETAL, together with dense arrays of CPV cells, could lead to system costs of around $1/Wp and hence, electricity costs below 10 ¢/kWh. Such low costs would clearly enable solar energy to compete with fossil fuel as a power source for electricity production. For this reason, it will be concluded that PETAL, by virtue of its large size, flexible optics, and ideal location, can provide a valuable laboratory facility for the study of such possibilities. In Part 2, we shall outline the technical steps we have already taken in order to prepare PETAL for CPV research and development. In particular, we shall show how the optical properties and tracking accuracy of such a large construction were studied, and some preliminary ray-tracing results for the design of a suitable second-stage optical flux homogenizer.

**VERY LARGE DISHES AND ECONOMICS**

The original motivation behind CPV systems was to try and offset the high cost of PV material by employing small areas of PV cells together with equivalently large collecting areas of low-cost lenses or mirrors. But there is a cost penalty to be paid in increased complexity. For, unlike a static PV system, which may be as large as we like for little, if any, increase in complexity, each CPV module requires its own tracking motors, guidance system, and possibly also a cooling system. For this reason, it makes the best economic sense to try and design a module which provides the maximum number of watts per amount of complexity. This is the motivation for going to very large dishes.

PETAL is a modification of a dish of Australian design that was originally intended for solar-thermal purposes [1], where large-area solar collectors are the norm [2]. In a study that was recently performed for the Task VIII PV Specialist Group of the International Energy Agency [3] (a group which studies the technical and economic feasibility of installing GW-size PV plants in various desert regions), we simulated the performance of a 1 m² dense array of SunPower CPV cells, illuminated by a 400 m² parabolic dish at Sede Boqer, Israel. Assuming that the cells are actively cooled so as to maintain a temperature of 60° C, the simulation indicates that the total system efficiency would be 16.5% and that each module would produce an annual AC energy output of 154 MWh (equivalent to a 93.4 kWp static PV array of non-concentrator PV modules at the same location).
System costs

Cost estimates were performed for a 30 MW CPV system, comprising 320 PETAL-size dish units. The following cost breakdown was obtained [3]:

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost ($/Wp)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dish units</td>
<td>0.4872</td>
<td>33.3%</td>
</tr>
<tr>
<td>PV modules</td>
<td>0.0910</td>
<td>6.2%</td>
</tr>
<tr>
<td>Inverters</td>
<td>0.3373</td>
<td>23.1%</td>
</tr>
<tr>
<td>Shipping</td>
<td>0.2677</td>
<td>18.3%</td>
</tr>
<tr>
<td>Project handling</td>
<td>0.2785</td>
<td>19.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.4617</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Now this list of costs could itself comprise the subject of an entire presentation. But it would not be very illuminating, because a number of site-specific assumptions have been made. Our purpose in showing the results of this particular set of calculations is: (a) to illustrate that system costs of around $1/Wp are feasible with CPV systems of this size; (b) to give an indication of where the big costs are; (c) to demonstrate that the CPV module is indeed a relatively small fraction of the total cost.

Operation and maintenance costs

It was also concluded [3] that, in spite of the complexity of such systems, their total operation and maintenance costs should be low for a number of reasons. First, experience with large solar-thermal power plants (at the 10-100 MW scale) [2], indicates that O&M costs of 1-2% of the capital cost are reasonable. In fact, for a CPV system there are no turbines to maintain: only sun trackers and mirrors.

Secondly, the parasitic energy costs needed to pump cell coolant through a CPV system may be largely recoverable by utilizing the thermal energy for some associated process. After all, since this energy is already pumped and piped, it could be delivered at no cost to an on-site user.

Thirdly, the possibility of serious cell degradation takes on a new and hardly significant aspect when it is realized that the 1 m² CPV module itself represents a relatively small part (both in size and cost) of the entire 400 m² dish unit. One could therefore think in terms of replacing modules periodically and, at the same time, taking advantage of improvements in technology, both to upgrade the power rating of the system and to recoup degradation losses [3].

PETAL AS A RESEARCH FACILITY

The above outline, in so far as the assumptions are realistic, clearly indicates that an attractive path toward fossil-competitive PV power may be via the employment of large parabolic dishes, the size of PETAL. We have emphasized the words “the size of” because PETAL, by design, is far too complex a facility to provide the basis of a cost-effective CPV system. However, by virtue of its large aperture area (which can always be reduced for experimental purposes), its variable concentration ratio, and location (on a desert plateau, at a university research institute, 2 hours drive from an international airport), PETAL constitutes an ideal research facility for studying a wide variety of technical aspects associated with optimizing CPV systems. For this reason, the remainder of this presentation will address a number of those aspects that have been studied prior to “adding a CPV module” to PETAL.

Optical properties of PETAL

PETAL’s mirror panels consist of rear-silvered “white” glass, of thickness 1 mm, glued to a fiberglass substrate. Wire-frame space trusses are used to help preserve the paraboloidal shapes of each of the 36 different panel types. The specula reflectance of the clean mirror glass, when measured using a standard reflectometer, was 0.94 before gluing.

The quality of PETAL’s image was measured in a variety of ways, mostly by analyzing the brightness distribution on a white screen mounted at the focus on a central mast (Fig. 1). For this purpose we employed a b&w CCD camera, with high sensitivity and good linearity. Measurements were performed with PETAL in its sun-tracking mode, and with the CCD camera mounted rigidly on the dish surface, pointing at the screen.

In chronological order, our first two studies of image quality were performed at night, by pointing PETAL at a full-moon (the angular size of which is conveniently similar to that of the sun) and at the planet Jupiter. It was found that 90% of the image intensity resided within circles of radius r = 0.26 m and r = 0.22 m, respectively.

Our third method for assessing the image quality of the entire dish involved removing the white screen from PETAL’s focus and imaging the 3-D light caustic reflected...
off dust particles in the air. For this purpose the CCD camera was carefully noted on the ground and the position of PETAL was carefully noted at the moment the CCD image of the caustic was made. At a later time, with dish and camera in their same positions, but with the sun elsewhere, a “ruler” with graduation marks every 10 cm was inserted into PETAL’s central mast and a second image was made. Superposition of these two images then enabled a quantitative analysis to be made of the light distribution within the caustic. The result indicated that 90% of the flux passes through a “neck” of radius \( r = 0.23 \) m (Fig. 2).

Our fourth series of tests was performed with the white screen back in place at PETAL’s focus. For this series, all 216 mirror panels were covered over except for the one to be tested. PETAL was set to track the sun on clear days, and each panel was successively exposed for characterization and then re-covered. Computer files were made of the resulting intensity distributions for each of the 36 panels that constitute one hexant of PETAL’s entire mirror surface (Fig. 1). Parallel measurements were made of the normal direct, and sky diffuse components of the incoming solar radiation, so that all images could be uniformly normalized. Each image file was characterized by the standard deviation parameter \( \sigma \) for its equivalent Gaussian distribution, and by the coordinates of its center. For all 36 panels in their “as is” alignments, the computer indicated that their combined image would contain 90% of its intensity within a circle of radius 0.25 m. If all 36 panels would be perfectly aligned, the image circle would be reduced to \( r = 0.18 \) m. This corresponds to 14 mrad in angle or a geometric concentration ratio of about 4050X.

It is worthy of note that the mirror panels were hand-glazed \textit{in situ}, with varying amounts of care being taken by the, largely volunteer, group of students who performed the work. For this reason, the optical quality varies quite considerably from panel to panel. However, for the best panels, 90% of the flux intensity was found to reside within a circle of radius \( r = 0.11 \) m. This indicates that, with suitable care in the glazing process, PETAL would be capable of producing a geometrical concentration of 10,000X.

Tracking accuracy of PETAL

PETAL tracks the sun about vertical and horizontal axes, under the control of a computer code that is based on astronomical data on the sun’s ephemeris. The code sends commands to an electro-hydraulic actuation system. According to the specifications, the resulting pointing error during sun tracking should never exceed ±2 mrad. PETAL’s hydraulic system provides independent corrections to its azimuth and elevation according to an algorithm that takes into account a variety of possible complications during the dish’s operation in automatic mode. Corrective action is performed according to a prescribed constant level of angular error (Fig. 3), which may be different for azimuthal and altitudinal corrections. The time intervals between successive corrections are functions of the time of day and day of the year.

In order to provide a precise characterization of PETAL’s tracking accuracy, use was again made of a CCD camera rigidly attached to the dish surface. This time the camera was aligned parallel to the optical axis of the dish so that it could view the sun during the tracking process. A computer sampled the signal from the camera at a frequency of 30 frames per second. This frequency is high enough for resolving the dynamics of individual corrective actions (Fig. 3), and also of detecting mechanical vibrations with frequencies up to about 5-10 Hz. Each successive pair of sun images was used to calculate the angular difference between them. The corresponding angular resolution of this method was, experimentally, found equal to 0.007 mrad both in azimuth and altitude. The resulting tracking precision of PETAL was found to be ±1.7 mrad, i.e., about 0.1 degree of arc. In fact our experimental method turned out to be so sensitive that it revealed some important peculiarities in PETAL’s tracking algorithm. Notably: mechanical vibrations with frequencies 2.3 Hz and 9 Hz, and amplitudes as small as 0.05 mrad were detected.

A flux homogenizer for PETAL

The intensity distribution produced by a 10,000X paraboloid is nowhere near uniform enough to serve as a suitable source of illumination for CPV cells. We therefore plan to employ secondary optics in PETAL’s focal region in order to \textit{deconcentrate} the light from the primary mirrors. This would be the mirror equivalent of a photographic \textit{condenser} lens. Such a device, known as a kaleidoscope [4], has already been studied in a context similar to ours [5]. It consists, as its name suggests, of a hollow tube with plane sidewalls having reflective internal surfaces. Flux from PETAL’s primary mirrors enters one end of the kaleidoscope and undergoes an appropriate number of reflections from the side walls in order to enable it to arrive with a more uniform intensity at a solar cell array located at the other end.

For the present study [6] ray tracing techniques were employed to calculate the intensity distributions over planes normal to, and at various distances along, the axis of a kaleidoscope. This enabled us to discover the optimal length for the homogenizing tube: too short, not enough light homogeneity; too long, too great a materials penalty and too high the absorption energy losses in the side walls. Kaleidoscopes of rectangular dimensions 1m x 1m,
1 m x 0.8 m, 1 m x 0.9 m, 0.96 m x 0.8 m, and 0.88 m x 0.8 m, with their entrance planes at distances 13.4 m and 13.5 m from the vertex of PETAL’s mirror paraboloid, were traced.

A variety of geometrical parameters were found to influence the homogeneity of the final distribution. For example, the effect of shading of the dish aperture by the receiver had a much greater effect on the irradiance distribution than might have been expected a priori. The receiver tube, closed at one end by the cell module, might shade only 0.24% of PETAL’s total aperture, but the effect of such shading was evident at every plane along the length of the kaleidoscope tube. These missing rays were found to cause a “hole” in the illumination distribution that could not be totally filled within any reasonably short tube length.

Secondly, the use of a slightly rectangular cross-section for the kaleidoscope tube was found to be superior to a square cross section, from the viewpoint of less wasted (i.e. non-illuminated) material at the entrance plane.

Our best run, to date, was for a kaleidoscope of length 2.44 m and cross-section 0.88 m x 0.80 m. Here the uniformity was found to be better than 95% over the entire cell plane. However, reasonable degrees of uniformity were obtained for shorter kaleidoscope tubes. For example, Fig. 4 shows the light distribution for a kaleidoscope of length 1.56 m and square cross-section 1m x 1m. The variation in intensity over the entire surface of the cell module (including the “hole” in the middle) is ±7% of the mean. However, by wiring the sub-modules in an appropriate series/parallel manner, this residual non-uniformity need not present a problem.

CONCLUSIONS

We argue that large parabolic dishes could render the economics of CPV potentially very attractive. To this end we discuss the properties of PETAL, an existing parabolic dish that has been specially designed as an extremely flexible laboratory facility for studying such possibilities. We invite the CPV community to come and make use of PETAL.

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REFERENCES


