# NEW CONCEPTS FOR STATIC CONCENTRATION OF DIRECT AND DIFFUSE RADIATION

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## SUMMARY

The rules for casting maximum energy on a cell placed in a static concentrator of minimum entry aperture are derived. A concentration of 9.13 for collecting the direct sunbeam throughout the year and of 4.5 for collecting diffuse light are upper bounds when using practical materials. Practical bifacial solar cells required to achieve those figures are presented. A prototype of concentrator with bifacial cells has been fabricated and its results are also presented. Based on the possible improvements of such a concentrator we arrived at a cost estimate of $3.19 W/peak.

## 1. INTRODUCTION

Conventional concentrating photovoltaic devices require some kind of tracking to keep the cells illuminated while the sun position varies. Furthermore, they do not use diffuse radiation which is important even in clear climates. The purpose of this paper is to develop the theoretical basis which show the feasibility of static concentrators as well as their operating limit; the extent to which diffuse radiation can be concentrated by those devices is also considered.

For that, the sun's direct beam is regarded as an extended source occupying the region of the sky in which it can be found at some moment throughout the year. Diffuse radiation is considered to be hemispherical and isotropic and the principles of non imaging optics (1) are used to analise the conditions leading to maximum concentration of the extended source. The concentrators are analised with respect to both radiation sources.

A concentrator made following this theory is also presented. As it is fully static and accepts a part of the diffuse radiation it can be handled very much like a conventional flat panel. We call it Flat Panel of Limited Aperture (F.P.L.A.)

## 2. MAXIMAL CONCENTRATION FOR DIRECT AND DIFFUSE LIGHT

Let S be a Lambertian source placed at the infinite with a constant angular density of energy flux $P_s$ on the direction normal to the source. The power collected by the concentrator is

$$W_e = P_s \int_{D_e} dx\ dy\ dp\ dq = P_s\ E_e \tag*{[1]}$$

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where integral $E_e$ is Winston's êtendue (1). Coordinates x y p q define a ray of the concentrator entry aperture. The two first ones are position coordinates, p and q are respectively the ray direction cosines with respect to x and y, times the refraction index n (usually n = 1 at the entry aperture).

It can be shown that the power reaching the collector is

$$W_c = P_s E_c \qquad [2]$$

where $E_c$ is the êtendue calculated at the collector. In general $W_c < W_e$ so that the optical intersect factor $I_o$ can be defined as

$$I_o = \frac{W_c}{W_e} = \frac{E_e}{E_e} \leq 1 \qquad [3]$$

To cast maximum power into the collector $E_c$ must be maximized. Its highest value occurs when isotropic incidence is achieved at the cell. This value is

$$E_{cm} = 2\pi n^2 A_c \qquad [4]$$

where $A_c$ is the collector's area. This value can be obtained only if the collector is a bifacial cell. With other collectors only hemispheric incidence is possible and the highest value of $E_c$ is only one half of that in Equation [4]. A degree of isotropy g can be defined as

$$g = \frac{E_c}{2\pi n^2 A_c} \leq 1 \qquad [5]$$

Concentrators with g = 1 are called optimal.

Three rules can be immediately derived to achieve maximum energy on the solar cell: a) to use bifacial cells, b) to submerge them in a transparent medium of highest n, c) to achieve the highest degree of isotropy for the light incident on the cell; for that any ray issuing from any point of the cell should reach the source.

Optical concentration can be defined as the ratio between the power in the cell placed in a loseless concentrator and the maximum power of the cell outside it. The latter value is

$$W_f = P_s E_f = P_s \int_{\Sigma_c} dx\,dy \int_{\Sigma_s} dp\,dq = P_s A_c A_s \qquad [6]$$

where $\Sigma_c$ and $A_c$ are the cell's surface and its area and $\Sigma_s$ is the region of existing rays in the plane p-q, i.e. the source region and $A_s$ is its area. The optical concentration is

$$C_o = \frac{E_c}{A_c A_s} = \frac{2\pi n^2 g}{A_s} \qquad [7]$$

Increasing the energy on the cell is not the only factor in reducing the concentrating system cost: the cost of the optical parts must also be reduced. For that it could be assumed that the concentrator entry aperture is flat and must have a minimum area for a given energy reaching the cell.

$$E_e = \int_{\Sigma_e} dx\,dy \int_{\Sigma_s} dp\,dq = A_e A_s \qquad [8]$$

where $\Sigma_e$ is the entry aperture and $A_e$ its area. We can now write

$$A_e = \frac{E_c}{I_o A_s} \qquad [9]$$

Since $E_c$ and $A_s$ are data, the maximum value of $A_e$ is obtained for $I_o = 1$. According to Winston these concentrators are called ideal. A fourth rule can be stated to decrease the concentrating system cost: d) all rays entering the entry aperture must be casted on the cell so that $I_o = 1$.

The concentrator's geometrical gain is $C_g = A_e/A_c$. This value can be related to the optical gain by using equations [7] and [8]

$$C_o = I_o C_g \qquad [10]$$

If a concentrator is oriented towards the intersection of the local meridian and the celestial equator, the region of the p-q plane where the sun can be found is represented in Figure 1. It constitutes the direct beam solar source. Its area $A_{bs} = 1.549$. Using this value in equation [7] for optimal concentrators $(g = 1)$ we obtain an upper bound for the direct beam optical gain. This value is 13.14 for n = 1.8 and 9.13 for n = 1.5.

The hemispheric solar radiation fills the full circle of unit radius in the space p-q. Its area is $A_{ds} = \pi$. The upper bound of diffuse radiation optical gain is $2n^2$. For n = 1.8 this value is 6.48 and for n = 1.5 it is 4.50.

## 3. PRACTICAL BIFACIAL SOLAR CELLS

All the preceding figures of concentration require bifacial cells. They would become reduced to one half if monofacial conventional cells were used. The availability of bifacial cells is a key point of optimal concentrators. A pilot production of 200 double diffused $p^+nn^+$ cells has been carried out. Efficiencies of 15.7% and 13.6%, front ($p^+$ side) and back ($n^+$ side) respectively, under AM1 illumination have been obtained at 28°C. At 7 X AM1 and 28°C front efficiency increases up to 16.5%, the fill factor being 0.75. At 23 X AM1 efficiency is still 14.7% and fill factor 0.65. A histogram of bifacial efficiencies (average front-back) appears in Figure 2. A yield of 80% has been obtained in our pilot production. An important feature of these cells is that they can be manufactured like conventional BSF cells. The only different step is the delineation of a metal grid on the back face. The technology for this step is not critical and can be the one used for the front grid. No mask alignment step is required.

## 4. BIFACIAL 2-D COMPOUND PARABOLIC CONCENTRATOR (CPC)

A static concentrator prototype has been made with a bifacial linear CPC profile (2) filled with mineral oil of n = 1.5. According to Winston the region of accepted rays is an ellipse of semiaxes n and sen $\phi_m$ where $\phi_m$ is the maximum acceptance angle for meridian rays. The geometrical gain of this concentrator is

$$C_g = \frac{2\,n}{\mathrm{sen}\,\phi_m} \qquad [11]$$

The value of $\phi_m = 30.19°$ leading to $C_g = 5.96$ has been selected so

Table I

FPLA Experimental characteristic

| | | |
|---|---|---|
| Entry aperture area | 2520 | cm |
| Cell area | 560 | cm |
| Geometrical concentration | 4.5 | X |
| Maximum power (AM1) | 13.3 | W |
| Open-circuit voltage | 9.15 | V |
| Short-circuit current | 1.82 | A |
| Fill factor | 0.737 | |
| Panel efficiency | 4.5% | |
| Effective area | 1680 | cm$^2$ |
| Effective efficiency | 7.3% | |
| Effective geometrical concentration | 3.00 | |

Table III

F.P.L.A. Cost estimate

(per 100 KW) market size

| | \$/m |
|---|---|
| Glas | 10 |
| Concentrator + optical surface (cold profiling + + optical surface) | 17 |
| Wiring etc. | 10 |
| Mineral oil | 60 |
| Labor | 27 |
| Total mounted concentrator | 124 |
| Mounted cells (at \$ 1000/m$^2$ x x 1/6) | 167 |
| Total panel | 291 |
| Panel efficiency | 9.1 % |
| Panel cost | \$ 3.19/Wp |

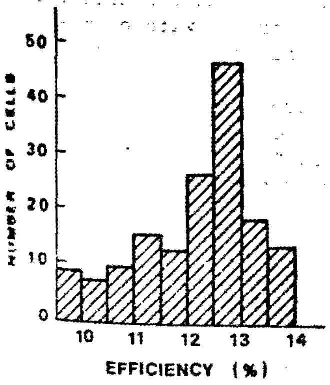

Fig. 2. Histogram of bifacial efficiency $(n_p+n_B)/2$.

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## Table II

**Breakdown of FPLA's Losses**

| | Prototype | Improved |
|---|---|---|
| Efficiency | 7.3 % | 9.1 % |
| Cell efficiency | 12 % | 12 % |
| Array efficiency | 11 % | 11.5 % |
| Optical efficiency | 66.4 % | 78 % |
| Collected radiation (diff. radiation losses) | 93 % | 93 % |
| Direct beam optical efficiency | 71.8 % | 84.7 % |
| Cover transmittance | 96 % | 96 % |
| Mirror efficiency | 74.8 % | 98.2 % |
| Average nums reflections | 1.5 | 1.5 |
| Mirror apparent reflectivity | 82.4% | 92 % |

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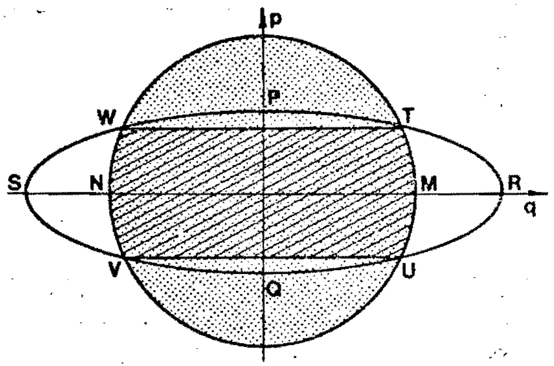

Fig. 1. Direct beam solar source (dashed). Diffuse solar source (dotted) and Concentrator's acceptance ellipse.

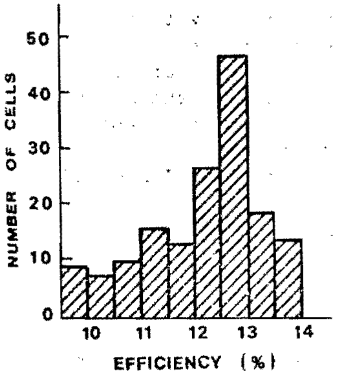

Fig. 2. Histogram of bifacial efficiency $(\eta_p+\eta_B)/2$.

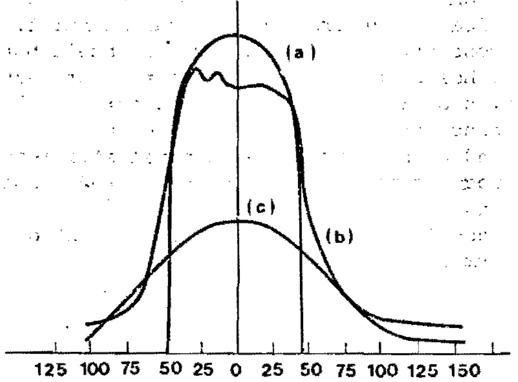

Fig. 3. Power output vs. azimut angle for: (a) concentrator's theory (b) concentrator's measurements and (c) flat panel measurements.

that the ellipse of accepted rays is circumscribed to the direct beam solar source, as represented in Figure 1. In that way the concentrator is ideal for this source, i.e. the direct beam is wholly accepted throughout the year. Since the concentrator is ideal the optical gain equals the geometrical gain and g can be obtained from equation [7]. Its value is $g_b = 0.64$ for the direct beam.

For diffuse radiation the concentrator is not ideal. Only rays inside region PTMUQVNW (see Figure 1) are accepted. The intersect factor is the ratio of this area to the area of the diffuse source (unit radius circle). This value is $I_{od} = 0.58$ representing the fraction of diffuse energy collected.

The optical gain for diffuse radiation according to equation [10] is $C_{od} = 3.44$ and the degree of isotropy is now $g_d = 0.76$.

The prototype we have fabricated includes 112 bifacial cells 2.5 cm long and 2 cm wide placed vertically in the linear bifacial CPC's. Modules of 7 cells in parallel are bonded in a copper-embedded fiberglass-charged polyester-resin holder which provides mechanical support and electrical connection. No additional encapsulation is required since the cells are submerged in an inert oil. 16 modules of this type are placed in 4 CPC high purity mirror-polished Al troughs and connected in series. The troughs are mounted in a hermetically sealed box with a glass cover and filled with a transparent mineral oil. The CPC's have a theoretical acceptance angle of 35°which corresponds to a geometrical concentration of 5.2. They have been truncated so that their height is only 7 cm resulting in a geometrical gain of 4.5.

The characteristics of this panel appear in Table I. A measure of photocurrent vs. incidence angle is presented in Figure 3. The measurement was made by tilting the concentrator towards the sun and then rotating it around a vertical axis. The expected theoretical curve is also drawn showing good agreement for the acceptance angle.

## 5. DISCUSSION AND CONCLUSSIONS

At present we do not know if the theoretical limit of 9.13 for the direct beam optical concentration can be reached. A practical concentrator with optical concentration of 6 can be built. A concentrator with geometrical concentration of 4.5 has been built but a defect in the design of the cell holder has reduced the intersect factor so that an apparent concentration of 3 must be considered for normal incidence. With that value of the concentration in Table II we have done a breakdown of the panel losses and we have predicted a panel efficiency of 9.1% in an improved panel. Cost estimate for medium size production is presented in Table III, predicting a cost of $3.19 W/peak.

We conclude that the concepts presented here can be considered as short-term cost reducing.

## REFERENCES

(1) W.T. Welford and R. Winston, The Optics of Non-imaging Concentrators, Academic Press, New York 1978.
(2) R. Winston and W. Hinterberger, Solar Energy, 17, 255 (1975).

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