Experimental Energy Yield in 1.5× and 2× PV Concentrators with Conventional Modules

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Low concentration devices along with standard (one sun) modules represent an attractive option to reduce the cost per kilowatt-hour in photovoltaic installations. This paper deals with the energy gains obtained over a year by two of such devices: a 2× V-trough concentrator and a 1.5× single flat mirror structure. The experiment was mounted on a two-axis tracking system located in Arguedas (northern Spain). Due to various optical and electrical phenomena, the energy gain is notably lower than the geometrical concentration. We have conducted a theoretical analysis of these phenomena and quantified the energy loss associated with each. Daily and monthly energy gains show an influence of daylight clearness index on energy output. In view of this effect, and taking into account a possible increase in degradation of the photovoltaic modules due to high working temperatures and hot-spots, the viability of these concentration devices is far from being clear.

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INTRODUCTION

The use of low concentration devices in photovoltaic systems has been proposed as a way to reduce the price of photovoltaic energy. Some concentrators are composed of parabolic reflectors, which provide concentration ratios of up to 5×.1–3 However, the combination of conventional photovoltaic (PV) modules with plane mirrors represents a simpler way to obtain low concentration devices, with a geometric concentration of two or less. The use of stationary flat reflectors with standard PV modules has been studied,4,5 and it has been shown that, at high latitudes, the annual output from modules can be increased by 20–25%.4 To improve the functioning of these devices further requires the use of some kind of solar tracking in order to maintain uniformity of irradiance over the modules.

The viability of these concentration devices depends not only on the final energy yield but also on the degree of module degradation due to the increased irradiance and operating temperature resulting from the concentration. To the best of our knowledge, manufacturers do not currently guarantee standard modules if they are used with concentrators, and this position is presumably due to uncertainty about the long-term behaviour of their modules under such conditions. With regard to yield, the energy gained in low
concentrating systems is less than the geometric concentration because of optical phenomena, such as loss of reflection from dirty mirrors and failure to concentrate diffuse radiation, and electrical phenomena, such as an increase in the operating temperature of PV cells and losses in series resistance. In order to improve performance of modules used with concentration, modifications, such as the use of a winged-aluminium heat-sink on the module underside, the use of half-cells rather than whole cells, and better stringing of the modules, have been proposed. However, modified modules are more expensive per unit area than a standard one-sun module.

The available literature on flat-mirror tracking concentrators with standard PV modules is mainly concerned with devices of geometric concentration of the order of two and with the corresponding energy gains principally on clear days. The experimental gains are between factors of $1/N^4$ and $1/N^5$, or between $1/N^5$ and $1/N^7$. There are also reports of energy gains over the period of a year, calculated by simulations: a factor of 1.37 for Recife (Brazil), 1.56 for Perth (Australia) and 1.34 for Boqer (Israel). The only reported studies of experimental gains over a year derive from concentrators installed in Widderstall, Germany, (1.45) and Manfredonia, Italy (1.58). These gains are calculated relative to a fixed system of PV modules and do not differentiate between the gain resulting from the mirrors and that resulting from the tracking system.

The work reported here is an experimental analysis of the energy gains measured in two geometric concentration devices, of $1/N^4$ and $2/N^5$, with standard PV modules set up in Arguedas, northern Spain. The study period was a whole year. We analyse and quantify the losses associated with each of the phenomena responsible for the difference between the value of geometric concentration and the final energy gain obtained. Both the concentrators and the reference system were mounted onto the same tracking platform, and so the measured energy gain is independent of that provided by the tracking system.

**THEORETICAL BACKGROUND**

**Optical considerations**

For low concentration, the V-trough concentrator, which consists of flat mirrors on either side of the photovoltaic module (Figure 1a), is the most widely used. This type of device can achieve geometric concentration superior to $2\times$.

V-trough geometry is defined by two parameters: the *trough angle*, $\psi$, and the *geometric concentration*, $C$, which is the quotient of the trough aperture, $A$, and the absorber (PV module) width, $a$, (1):

$$ C = \frac{A}{a} \quad (1) $$

To avoid losses due to dispersion and hot-spot phenomena, incident irradiation must be evenly distributed over the absorber surface. For an ideal concentrator perfectly aligned with the Sun, this condition leads to the following relation for a single reflection (ray 1 in Figure 1a):\(^\text{12}\)

$$ C = \frac{A_1}{a} = 1 + 2\cos2\psi \quad (2) $$

![Figure 1. (a) Geometry of V-trough concentrator; (b) typical angular acceptance function for V-trough cavities](https://example.com/v-trough.png)
Note that the term $2\cos 2\psi$ represents the energy added by the two mirrors, so in the case of a single-mirror device, this term is $\cos 2\psi$. To maintain uniformity of irradiance even when alignment is not perfect, real concentrators use longer mirrors than those derived from Expression (2). In this way, it is possible to give the concentrator an angular aperture, $\theta_u$, which is the maximum angle of incidence for which irradiation of the receptor is uniform (ray 2 in Figure 1a). This means that surface area for capture is greater ($A_2 > A_1$), and so the geometric concentration is higher:

$$C = \frac{A_2}{a} > 1 + 2\cos 2\psi$$  \hspace{1cm} (3)

For a given angle of incidence, $\theta_i$, the angular acceptance, $F(\theta_i)$, is defined as the fraction of the rays which cross the entrance aperture that reach the receptor. This function is of the form indicated in Figure 1b and, for angles less than the angular aperture has a constant value given by:\textsuperscript{12}

$$F(\theta_i) = \frac{1 + 2\cos 2\psi}{C} \quad |\theta_i| \leq \theta_u$$  \hspace{1cm} (4)

Optical concentration, $C_{op}$, is defined as the quotient of the irradiance in the receptor and in the entrance aperture. Note that, in photovoltaic terms, this is equivalent to the quotient of short-circuit currents in the module when it is placed inside and outside the concentrator. With ideal mirrors (reflectivity = 1), the optical concentration is equal to the product of the geometric concentration and the angular acceptance function. Thus, for angles of incidence which provide uniform irradiance:\textsuperscript{12}

$$C_{op}(\theta_i) = 1 + 2\cos 2\psi \quad |\theta_i| \leq \theta_u$$  \hspace{1cm} (5)

In real concentrators, however, the optical concentration is diminished because the mirror reflectivity, $\rho$, is less than one. To accommodate this, Equation (5) can be written in the form:

$$C_{op}(\theta_i) = 1 + 2\rho \cos 2\psi \quad |\theta_i| \leq \theta_u$$  \hspace{1cm} (6)

Optical efficiency, $\eta_{op}$, is defined as the relationship between optical and geometric concentrations. When the device receives only direct irradiance with an angle of incidence inside the acceptance angle, optical efficiency is given by the following expression:

$$\eta_{op}(\theta_i) = \eta_B(\theta_i) = \frac{1 + 2\rho \cos 2\psi}{C} \quad |\theta_i| \leq \theta_u$$  \hspace{1cm} (7)

However, when the incident irradiance contains a certain diffuse fraction, $F_D$, the optical efficiency is given by

$$\eta_{op} = (1 - F_D)\eta_B + F_D\eta_D$$  \hspace{1cm} (8)

where $\eta_B$ and $\eta_D$ are the optical efficiencies for the direct and the diffuse irradiance, respectively.

The value of $\eta_B$ can be obtained from Expression (7). The value of $\eta_D$ for V-trough devices can be obtained, in an approximate way, from the following expressions:\textsuperscript{13}

$$\eta_D \approx \frac{1}{C} \rho^2$$  \hspace{1cm} (9)

$$n_d \approx a + b(m - 1)$$  \hspace{1cm} (10)

$$m = \frac{\sin^{-1}(\frac{1}{\rho})}{\psi}$$  \hspace{1cm} (11)

In Expression (9), the term $n_d/C$ represents, for diffuse radiation, the average number of reflections which rays experience before arriving at the receptor. The coefficients $a$ and $b$ depend on the geometric concentration and their values for $C = 2\times$ are 0.149 and 0.148, respectively.\textsuperscript{13}

It follows that optical concentrations for direct, diffuse and global irradiation are given, respectively, by

$$C_{opB} = C\eta_B; C_{opD} = C\eta_D; C_{op} = C\eta_{op}$$  \hspace{1cm} (12)

Another aspect to take into account is that the mirror reflectivity depends significantly on wavelength, and this means that optical concentration depends on the solar elevation angle, $\gamma$. As the solar elevation angle increases, the air mass diminishes, the solar spectrum is displaced towards the ultraviolet, and there is a decrease in the reflectivity of silvered mirrors. Figure 2 shows the spectral reflectance of silver,\textsuperscript{14} the spectral response of a BP ‘Saturno’ cell,\textsuperscript{15} and the global spectral irradiance, $G(\lambda)$, on a sun-tracking surface for different angles of solar elevation\textsuperscript{16} during a sunny day.

Electrical considerations

The efficiency of a photovoltaic cell, $\eta$, decreases with operating temperature, $T_c$. This dependency is described in Reference \textsuperscript{17} by the equation

$$\eta(T_c) = \eta^* \left[1 + \frac{dP}{dT_c} (T_c - T_e)\right]$$  \hspace{1cm} (13)
where superscript \(^*\) means standard test conditions, STC \((G^* = 1000 \text{ W/m}^2; T_c^* = 25^\circ C)\), and \(dP/dT_c\) is a characteristic of each photovoltaic technology. For crystalline silicon, \(dP/dT_c \approx -0.45\%/^\circ C\). Cell operating temperature is a function of ambient temperature, \(T_a\), incident irradiance, \(G\) and wind speed, \(V_w\).

Providing \(T_c\) is constant, the efficiency of an ideal solar cell tends to increase with irradiance. This is a second-order effect due to open circuit voltage increase that is not considered in Equation (13). In a real cell, however, although open circuit voltage increases logarithmically with irradiance, the maximum power point voltage is limited by the voltage drop in series resistance and tends to saturate at higher light levels. The light level at which efficiency is maximum depends on the design of each module, but in conventional modules, maximum efficiency is normally achieved at irradiance values not far from 1000 W/m\(^2\).

The above phenomena are responsible for the fact that, on those days with the highest clearness index, the gain in power output obtained with concentrator devices turns out to be much lower than the optical concentration measured.

**THE ARGUEDAS SET-UP**

The experimental set-up (Figure 3) was located in Arguedas (Navarra, north Spain). The usual horizontal and optimum tilt isolation values for the site are about 1670 and 1760 kWh/m\(^2\), respectively. Average noon time ambient temperature is approximately 18.5\(^\circ C\). The structural framework was equipped with two-axis tracking, so that the structure was always facing the theoretical sun position. On this structure were assembled 24 BP 5170S photovoltaic modules, which had been selected so that their I–V characteristics were similar. The modules were divided into three series of eight modules each. In one series, we mounted a flat-mirror V-trough device with geometric concentration of approximately 2\(^*\) (~\(C = 2.13 \times \), \(\psi = 30^\circ\))\(^\dagger\). In another series, we mounted flat-mirrors to only one side of the modules and thereby achieved a geometric concentration of approximately 1.5\(^*\) \((C = 1.57 \times , \psi = 30^\circ)\). The other series had no concentration, and served as a reference system to evaluate the energetic behaviour of the concentrators. The arrangement of these concentrators and the reference system

\(\dagger\)Values of \(C = 1.57 \times \) and 2.13, instead of \(C = 1.5 \times \) and 2\(^*\), provide for a 2\(^\circ\) tolerance in tracking angle.
on the same tracker allowed us to determine the real energy gains obtained, without such gains being affected by energy gains due to tracking. Each series was connected to an INGECONSUN 2.5 kW inverter, in which the power output was recorded. The set-up was equipped with calibrated photovoltaic cells which enabled us to measure the irradiance at each of the series. Furthermore, the temperatures of various cells distributed throughout the three series were measured using PT100 temperature sensors (see Figure 3). Irradiance and temperature measurements were made at 1 s interval and average values were recorded at 30 s.

The study period was January–December 2004.

Optical aspects

From the irradiance measured in each series of modules it is possible to obtain the corresponding real optical concentrations. Figure 4 shows, for the $C \approx 2 \times$ concentrator, the optical concentration during 2 days with different clearness index ($K_{Td} = 0.74$ and 0.21). The mirrors were clean for these measurements.

On both days, the value of global optical concentration remained practically constant throughout the days ($C_{op} \approx 1.75$ and 0.96, respectively). From the mean global optical concentration and proportion of diffuse radiation, it is possible to make an empirical estimate of the optical concentration factors for direct and diffuse radiation in the $2 \times$ concentrator. These values are given in Table I. Note that a $C_{opD}$ value of 0.91 implies that the amount of diffuse irradiation received by the modules in the $2 \times$ concentrator was over 10% less than that received in modules without concentrators. Due to this influence of diffuse radiation, the measured values of global optical concentration during 2004 varied between 1.8 and 0.91. As shown in Figure 5, this degree of variation is similar to that which can be observed on a day with variable cloudiness.

The values of $\eta_B$ and $C_{opB}$ in Table I are similar to those obtained from Equations (7) and (12) on the basis of the mirror reflectivity given in manufacturer’s data ($r = 0.83$). On the other hand, from Equation (9), assuming average number of reflections for diffuse radiation is given by Equations (10) and (11), $\eta_D$ becomes 0.46. This value is slightly higher than that obtained empirically. From the two values of optical concentration for direct and diffuse radiation, the global optical concentration can be calculated as a function of the diffuse fraction of the radiation, $F_D$, Equation (7).

As with the V-trough concentrator, empirical estimations of values of optical concentration for direct and diffuse irradiation can be made for the $1.5 \times$ concentrator. These results are given in Table II.

The amount of diffuse radiation which reaches the modules in the $1.5 \times$ concentrator is over 40% less than that which arrives at a module situated outside such a concentrator ($C_{opD} = 0.57$). In this case, the global

![Figure 4](image-url)  
Figure 4. Optical concentration, $C_{op}$, in the V-trough cavity during two different days: a sunny day ($K_{Td} = 0.74$, $F_D = 0.1$) and a foggy day ($K_{Td} = 0.21$, $F_D = 0.95$)

![Figure 5](image-url)  
Figure 5. Incident irradiance and optical concentration values ($C \approx 2 \times$) throughout on a day with variable cloudiness (2004/02/28)

<table>
<thead>
<tr>
<th>Concentrator</th>
<th>$\eta_B$</th>
<th>$C_{opB}$</th>
<th>$\eta_D$</th>
<th>$C_{opD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C = 2 \times$ ($C \approx 2$)</td>
<td>0.86</td>
<td>1.83</td>
<td>0.43</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table I. Experimental values for the optical efficiency and optical concentration of the V-trough cavity
optical concentration measured during 2004 varied between 1.34 and 0.65.

As mentioned before, solar elevation angle affects solar spectrum which, in turn, affects mirror reflectivity and, hence, optical concentration. Figure 6 plots experimental optical concentration versus solar elevation for the $2 \times$ concentrator. The first varies from 1.8 to 1.6 while the second varies from 32° to 68°. All the measurements of $C_{op}$ correspond to moments near noon on clear days, when the incident irradiance was approximately 1000 W/m$^2$.

The above experimental values of optical concentration for diffuse and direct irradiation were obtained with clean mirrors. However, measurements taken from the same set-up before and after mirror cleaning demonstrate that the dirt that accumulates on the mirrors causes a loss of nearly 3%.

**Electrical aspects**

From the measurements taken at the Arguedas set-up, we obtained an empirical relationship between mean cell temperature, $T_c$; global incident irradiance, $G$ and wind velocity, $V_w$ (Figure 7a).

$$\frac{T_c - T_a}{G} = 0.0309 - 2.5 \times 10^{-3} V_w + 8 \times 10^{-5} V_w^2$$  (14)

The value of $T_c$ corresponding to $G = 800$ W/m$^2$, $T_a = 20^\circ$C and $V_w = 1$ m/s is a characteristic of a PV module and denominated the NOCT. Equation (13) gave us an NOCT value of 43°C, which is slightly lower than the 47°C specified by the manufacturer. Note that $T_c$ was measured by attaching resistance-based temperature sensors to the back of the module and that this method underestimates the real junction temperature by up to 3°C.

Figure 7b shows, for each series of modules, an estimation of the temperature rise (relative to ambient temperature) as a function of wind velocity. The values were obtained from Equation (13) for irradiance of 1000 W/m$^2$ in the module series without concentration. The effect of wind velocity on operating temperature is greater in the devices with higher levels of concentration. On the other hand, temperature in the $1.5 \times$ concentrator can be observed to rise more than 40°C above ambient temperature on occasions when wind
velocity is very low. In the 2× concentrator, the temperature rise can be up to 55°C (Figure 7b). Maximum temperatures measured in each concentrator during the year 2004 were 85°C for $C \approx 2 \times$ and 75°C for $C \approx 1.5 \times$. Such high temperatures can accelerate the process of encapsulant degradation, as has been reported by other authors.19

Furthermore, the existence in the modules of areas of non-uniform illumination caused by alterations (for example, dirt accumulation) to the surface of the modules or mirrors, can give rise to so-called hot-points.19 We visually observed the occurrence of such non-uniform illumination in our set-up. The probability of hot-spot occurrence increases with concentration level, since both the current circulating in the cells and the cell temperature are increased. By way of example, Figure 8 shows the daily evolution of temperature in different cells of the $1 \times$ and the $2 \times$ devices in a sunny day (Figure 8a and b, respectively). Transitory appearance of hot-spots is indicated in the figures. Hot-spots have an important effect on PV module degradation.20

Figure 8 also shows how the use of concentration increases the temperature differences between different points in these series of modules. This results in greater dispersion in the characteristic curves of the modules and, therefore, greater losses. With a view to reduce the temperature reached by modules subjected to concentration, the use of a winged-aluminium heat-sink on the module underside has been proposed.21

The influence of series resistance on module efficiency is demonstrated in Figure 9, which plots efficiency measurements against irradiance for each concentration level. Values have been extrapolated to a cell temperature of 25°C. In the absence of concentration, at $T_c = 25\, ^\circ\text{C}$ efficiency was 13.5%. With 1.5× geometric concentration, efficiency fell to under 13%. With 2× geometric concentration, efficiency dropped to about 12%. The use of half-cells rather than whole cells has been proposed as a method of reducing the generated current and thus series resistance losses.21

The combined effect of an increase in cell temperature and an increase in losses due to series resistance results in factors for maximum power gains of between 1-4 and 1-5 in the $C \approx 2 \times$ concentrator, whilst in the $C \approx 1.5 \times$ concentrator we did not observe gains above 1-2.

Once the influence of the diverse factors which affect power gain has been experimentally obtained as a function of the environmental conditions, it is possible to calculate the contribution of these factors to losses in output power at any given moment. As an example, Figure 10 presents the balance of powers in the two concentrators calculated for particularly favourable environmental conditions: $G_1 \times \approx 1000\, \text{W/m}^2$, $F_0 \approx 0-1$, $\gamma_s \approx 45^\circ$, $T_a \approx 10\, ^\circ\text{C}$ and $V_w \approx 3\, \text{m/s}$. The percentages are relative to the power obtained in the series without concentration. The calculated power gain in the 1.5× concentrator is around 22%. This value is slightly higher than the maximum power gain measured in that concentrator (≈20%). A possible explanation for the difference is that in the 1.5× concentrator
that obtained in the 1.5× device, the way in which the increases in losses are distributed differs. On the one hand, the 2× concentrator has a higher optical efficiency and so the increase in power loss due to the non-concentration of diffuse radiation is less than double relative to the C≈1.5× device. (In fact, loss increases were found to be similar with both devices.) On the other hand, the increases in module operating temperature and incident irradiance make the electrical efficiency of the 2× concentrator lower than that of the 1.5× concentrator. Thus, the increase in module power losses due to operating temperature and series resistance are more than double (nearly three times greater) in the 2× concentrator relative to the 1.5× concentrator. Overall, the device with 1.5× geometric concentration is more affected by the proportion of diffuse radiation than the 2× device, whilst the latter is more affected by temperature and global irradiance.

**Energy gain**

Figure 11a plots the daily clearness index and Figure 11b the daily energy gains for the two concentrators.
CONCLUSIONS

Experimental results obtained over a year in two geometric concentration devices, of 1.5× and 2×, set up in Arguedas (northern Spain) have been presented. Maximum power gains in the 2× concentrator were between 1.4 and 1.5, whilst in the 1.5× concentrator we did not observe gains above 1.2. Annual energy gains in both concentrators were by factors of 1.35 and 1.12, respectively, as a consequence of the low values of concentration for diffuse irradiation.

The elevated temperatures that modules can reach, especially in the summer, can accelerate module degradation. In addition, non-uniformity of module irradiation, as a consequence of mirror surface irregularities or shadows, can provoke hot-spots that lead to deterioration of cells, the encapsulant or both. The temperature reached at hot-spots and, so, the seriousness of hot-spots increases with concentration. Thus, it is not surprising that most of manufacturers will not
guarantee their modules if they are subjected to concentration.

The cost increase associated with the use of concentrators, in conjunction with the relatively low energy gains obtained and the possible problems of module degradation, means that the economic viability of these devices, when used with conventional one-sun modules, may be limited. Modules made of thin films, which have been shown to be more tolerant of high temperature and non-uniformity of radiation, may represent another option to be considered for use with low concentration devices.

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REFERENCES