ABSTRACT: The purpose of the work is to develop a cost effective semistationary CPC concentrator for a string PV-module. A novel method of using annual irradiation distribution diagram projected in a north-south vertical plane is developed. This method allows us easily to determine the optimum acceptance angle of the concentrator and the required number of annual tilts. Concentration ranges of 2-5x are investigated with corresponding acceptance angles between 5 and 15°. The concentrator should be tilted 2-6 times per year. Experiments has been performed on a string module of 10 cells connected in a series and equipped with a compound parabolic concentrator with $C = 3.3X$. Measurement show that the output will increase with a factor of 2-2.5 for the concentrator module, compared to a reference module without concentrator. If very cheap aluminium reflectors are used the costs for the PV-module can be decreased nearly by a factor of two.

Keywords: Concentrator, Thermal performance, Cost reduction

1. INTRODUCTION

The cost for solar cells today is very high, and methods for reduction of the cost for PV technology are of great interest. One way is to use reflecting optics for increasing the irradiation on the solar cells. This may imply decreased cost for the delivered energy since reflectors with good quality are available to a fraction of the cost of solar cells.

The purpose of this work is to develop a cost effective semistationary compound parabolic concentrator (CPC) for a string PV-module for use in Swedish (latitude 60°N) climate. Concentration ranges of 3-5X were investigated with corresponds to acceptance half-angles between 6 and 15°. With such low concentrations, standard PV cells can be used, provided that cells with low series resistance are used. The principal shape of the CPC, designed for collecting radiation from the angular interval $\pm \theta_a$, where $\theta_a$ is the acceptance half-angle, is shown in Fig. 1.

2. CONCENTRATOR DESIGN
In this analysis, the concentrator is assumed to be linear (two-dimensional) with the concentrator axis extending from east to west. In order to study the irradiation distribution for determine the optimum concentrator design, the annual irradiation distribution is summarised into an irradiation projection diagram showing the annual cumulative irradiation distribution projected in a vertical plane extending from north to south [1]. Such a diagram, showing the irradiation distribution for Stockholm, latitude 59.4°N, is shown in Fig. 2. The south projection angle $\theta_{P,NS}$ is then the angle between the projected radiation and the south horizon. Since most of the annual irradiation is incident from the angular region $5^\circ \leq \theta_{P,NS} \leq 65^\circ$, this means that a fully stationary EW-aligned concentrator should have an acceptance half-angle of approximately $30^\circ$.

![Figure 1. Principal drawing of the compound parabolic concentrator, showing the acceptance half-angle $\theta_a$.](image)

The contribution of direct solar irradiation in Fig. 2 is concentrated to different angular regions during different periods of the year. The degree of concentration can therefore be increased if semistationary concentrators, designed for changing tilt 2-6 times per year, can be used. In Fig. 3 has the annual irradiation been divided into different seasonal periods, where each period has its direct irradiation concentrated to an angular interval of $\Delta \theta_{P,NS} \approx 20^\circ$. This means that if the concentrator tilt is changed 6 times per year, an acceptance half-angle of $\theta_a \approx 10^\circ$ is satisfactory, which in practice means that a much higher concentration can be used compared to a design which is stationary the year around.
A theoretical study was performed on the possible increase of irradiation onto the solar cell with semistationary concentrators, tilted six times per year, compared to a stationary solar cell without concentrator. In the calculations, a specular reflectance of $\rho = 0.8$ was assumed and the diffuse irradiation was assumed to be isotropic. As seen in Fig. 4, it is possible to increase the annual irradiation on the solar cell more than 140% by choosing an acceptance angle in the range $6^\circ$ - $10^\circ$.

In the calculations the concentrator height was set to 5 times the width of the solar cell which means that the concentrator has to be truncated. In theory the concentration, and thereby possible increase of irradiation on the cell, therefore can be larger than indicated in Fig. 4 if a higher
A concentration cell is usually used. In practice, however, a very high concentrator is difficult to manage, and a concentrator height of 5 times the width of the solar cell was estimated to be near the practical limit.

Increased annual irradiation compared to a single cell

![Graph showing increased annual irradiation](image)

**Figure 4.** Annual increase of irradiation on a PV cell with CPC compared to a single cell. The CPC is assumed to change tilt 6 times per year while the single cell is stationary.

### 3. EXPERIMENTAL SET UP

A string module of 10 square crystalline Si cells (10 X 10 cm) connected in series was designed [2]. During September 1997, three different geometry’s of the string module was tested:

1. A single module, tilted 45° to the south (reference)
2. A string module equipped with a CPC with concentration C = 2.55X (θ_a = 23.5°). The CPC height was 5 times the cell width.
3. A string module equipped with a CPC with concentration C = 3.30X (θ_a = 15°). The CPC height was 5 times the cell width, see Fig. 5.

The purpose of the measurements was to investigate the effect of increased cell temperature and uneven irradiation distribution in the case when the solar cells is equipped with concentrators and comparing the measured output with the calculated increase of irradiation onto the concentrator cells. The module equipped with a 3.3X CPC was equipped with a water tank on the back side, allowing cold water to cool the module. However, most of the measurements was done with the module not cooled.
The I-V characteristics of a reference module and the modules with CPCs was monitored. A sample result, showing the output from the module with a 3.3X CPC and the reference module during one day (September 28, 1997) is seen in Fig. 6. While the reference module has its maximum power output during noon, the concentrator module reaches its maximum power at 10.40 am - after this the increased temperature in the concentrator module starts to decrease the output power. At 13.40 (1.40 PM) cold water started to circulate behind the concentrator module which immediately increased the output power by approx. 15% for from the concentrator module. During this day, which had clear weather, the increase in output for the concentrator module was approx. 150% larger than for the reference. The ration between the output power from the CPC module and the reference module decreases before 9.00 am and 15.00 (3.00 PM) due to the finite length of the reflector trough which cause an uneven irradiation distribution on, and thus reduced output from, the concentrator module for skew incidence angles.

The role of module temperature on the module performance was investigated with momentary measurements during a day with clear weather. Results from four measurements on the concentrator module with a 3.3X CPC and the reference module which was cooled and not cooled respectively is shown in table 1. The module temperature is measured with a thermocouple, glued and insulated on the back side of the module. The increase in power output from the concentrator module compared to...
the reference is about 125% when the modules are not cooled and 140% when the modules are cooled. If the increase in output power is weighted with the incident radiation, both the cooled and not cooled case shows an increase in power output of about 130%. This is surprising since the non cooled concentrator module has a much higher temperature and thus larger expected module losses. Measurements shown in Fig. 7 however show that the drop in open-circuit voltage due to increased temperature is much lower when the cells is exposed for concentrated irradiation compared to the reference module exposed for one sun irradiation.

Figure 6. Output power from a string module equipped with CPC reflector with $C = 3.3X$ and a reference module during a day with clear weather (September 28, 1997). The module with CPC was cooled from 13.30 by cold circulating water on the back side of the module.

<table>
<thead>
<tr>
<th>C</th>
<th>Cooling</th>
<th>$T_{ambient}$</th>
<th>$T_{module}$</th>
<th>$I_{sun}$</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
<th>$V_{mp}$</th>
<th>$I_{mp}$</th>
<th>$P_{max}$</th>
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<tr>
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<td>30</td>
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<td>900</td>
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<td>4,11</td>
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<td>910</td>
<td>6,07</td>
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<td>4,32</td>
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<td>0,63</td>
</tr>
</tbody>
</table>

Table 1. Result from measurements during sunny conditions.
During the measurement period (September 16-30, 1997) the output from the (non cooled) module with a 3.3X CPC was 1.618 kWh while the output from the reference module was 0.734 kWh. This corresponds to an increase in output by 120% from the concentrator module compared to the reference module. Calculations show that this increase is about 20% lower than the increase in irradiation on the concentrator module compared to the reference. The difference depends both on differences in module temperatures and shading effects during skew incidence angles in the case of the concentrator module.

5. CONCLUSIONS

A prototype of a string module with concentrating CPC-reflectors will increase the annual module output with a factor of 2-2.5. If the higher output should be reached the module has to be tilted 4-6 times annually. To avoid too high losses due to high module temperatures when concentrators are used, the module temperature should be kept below approx. 75°C. The module then has to be cooled, which either can be done by passive or active cooling. This is planned to be investigated in the proceeding project.

The materials cost for the concentrator is around 140 ECU per m² of module area. If very cheap aluminium reflectors are used the costs for the PV-module can be decreased by a factor of two.

ACKNOWLEDGEMENTS
This work has been carried out in co-operation with Vattenfall Utveckling AB in the frame of the national solar electricity programme SOLEL 97-99 financed by NUTEK, the Swedish utility industry and NAPS Sweden AB.

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