Paper presented at North Sun'99, Edmonton, Alberta, Canada, August 11-14, 1999

ACTIVE COOLING OF LOW-CONCENTRATING HYBRID PV/THERMAL COLLECTORS

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Abstract

A series of measurements on the performance of solar cell string modules with low-concentrating CPC reflectors with a concentration factor C ≈ 4X have been carried out. To minimise the reduction in efficiency due to high cell temperatures, the modules were cooled. Four different way of cooling were tested:
1) The thermal mass of the module was increased, 2) passive air cooling was used by introducing a small air gap between the module and the reflector, 3) the PV cells were cooled by a large cooling fin, 4) the module was actively cooled by circulating cold water on the back. The best performance was given with the actively cooled PV module which gave 2,2 times the output from a reference module while for the output from the module with a cooling fin the value was 1,8.

Active cooling is also interesting due to the possibility of co-generation of thermal and electrical energy which is discussed in the paper. Simulations, based on climate data from Stockholm, latitude 59.4°N, show that there are good prospects for producing useful temperatures of the cooling fluid with only a slightly reduced performance of the electrical fraction of the PV thermal hybrid system.

1. Introduction

The current high cost of solar cells makes the use of reflectors for increasing the irradiation on to the PV modules of interest since the cost of reflector materials is, in general, considerably less than the cost for the modules. The use of booster reflectors is one technology that can be of interest since a single booster reflector can increase the annual output from the module in the order of 20-25% (Rönnelid *et al.,* 1997). With more advanced concentrator designs, such as the use of compound parabolic concentrators (CPCs), the annual output can be even higher (Rönnelid *et. al.,* 1998).

The efficiency of a PV module decreases with cell temperature, and for silicon solar cells this decrease can be calculated to 0.4 - 0.5 %/°C (Green, 1992). An increased irradiance on the module due to the use of concentrators implies an increased cell temperature and therefore decreased efficiency, unless the PV module is cooled. Investigation of techniques for efficient cooling of modules equipped with concentrators is therefore necessary.

2. Experimental set-up

In this study, symmetrical CPC concentrators with a concentration ratio C = 4X are used. The CPCs have an acceptance half angle of 10 degrees, truncated to a height of 45 cm. The modules used are string modules consisting of one row with 10 serial coupled X-Si cells, each cell with a size of 10 * 10 cm. The modules were specially designed by Gällivare Photovoltaics (GPV) in Sweden. To avoid large errors due to uneven illumination of different cells in the module during morning and evening hours, the reflectors were 2 m wide which means that they extend 0.5 m on each side of the PV module. A single PV module without concentrator was used as reference. The experiment was performed during the period July 19 - September 30, 1998. The experimental set-up is shown in fig. 1.

Four different ways of cooling the modules were tested:

Prototype 1) The <u>thermal mass</u> of the module was increased by having a small tank with 4.6 kg water in close contact with the back of the module. Since the increased thermal mass delays the heating up of the module during the day, the maximum module temperature occurs during thehours after noon. This is intended to increase the daily performance compared with a module with lower thermal mass.

Prototype 2) Passive <u>air cooling</u> was used by introducing a 2 cm air gap between the module and the reflector. This facilitates natural air circulation across the front surface of the module.

Prototype 3) The PV cells were cooled by a large <u>cooling fin</u>. The cooling fin, originally manufactured for cooling electronic equipment, was glued on the back of the module with a heat conducting glue.

Prototype 4) The module was <u>actively cooled</u>. The same water tank as for prototype 1 was used but cold water was continually circulated through the tank.

A logger was used to collect IV-characteristics and module temperature every 10th minute. From these data, the maximum efficiency of the module was calculated.

QuickTime™ and a
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are needed to see this picture.

Figure 1. Experimental set-up of CPC concentrators with PV modules for testing different methods for cooling the modules. Photo from Vattenfall Utveckling AB, Älvkarleby Laboratory, summer 1998.

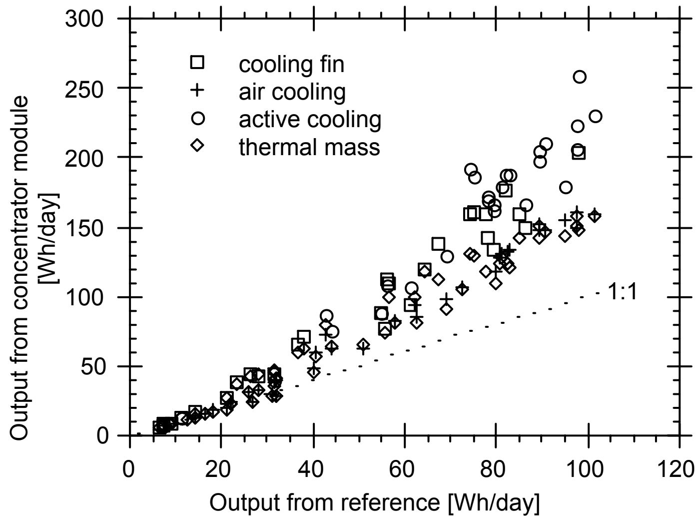
3. Experimental results

The different cooling techniques were compared by summarising the total electrical energy generated during the measurement period. This was compared with the energy generated by the reference module without concentrator during the same period. The result is summarised in table 1. The temperature shown in table 1 is the module mean temperature which is the measured temperature weighted with the generated power during the measurement period. It should be noted that all four modules were not used all the time; therefore the energy generated by the reference module is different for the different cases. The result is also shown in figure 2 showing the output from the concentrator modules as a function of the output from the reference module.

Table 1. Result from measurement of cooled concentrator modules during the period July 19 - September 30, 1998.

Concentrator module		Reference module			
Energy [kWh]	T_{mean} [°C]	Energy [kWh]	T_{mean} [°C]	Energy-ratio	No. of measurement days
Thermal mass 4,27	47,2	2,90	32,7	1,47	60
Air cooling 2,85	53,2	1,95	33,5	1,46	37
Cooling fin 2,58	38,8	1,41	32,2	1,82	29

Active cooling					
3,32	18,7	1,51	36,7	2,20	21



<u>Figure 2</u>. Input/output diagram showing the daily output from the concentrator modules *vs*. the output from the reference module. All measurement days are included in the diagram.

Table 1 and figure 2 show that the output from the actively cooled module is largest and the module with a cooling fin has the next best result. The output for the two modules with large thermal mass and air cooling is considerable lower.

The output from the concentrator modules is, in general, surprisingly low bearing in mind the relatively large concentration ratio of the CPCs. However, the weather in Sweden was not favourable during the measurement period with less than 90% of the global radiation compared to normal years. Since it is mainly the direct radiation that is lacking during periods with bad weather, this can influence concentrating systems rather strongly. Probably the acceptance angle was somewhat on the small side, thus giving undesirable reduction of the diffuse radiation in the near specular direction. The small acceptance angle also caused the collected radiation to be collected at incidence angles near the acceptance angle at noon. This brings the reflected radiation to be concentrated in regions at the edges on the PV-module near the reflectors. The concentration of radiation on a small area of the PV-cells implies large local electrical currents which reduce the output from the module, which can be seen as a slightly drop of the output during the hours round noon (figure 4). Therefore, slightly larger acceptance angles will be used in future work. However, the approximate effect of different cooling techniques on the output should also be valid for more normal conditions.

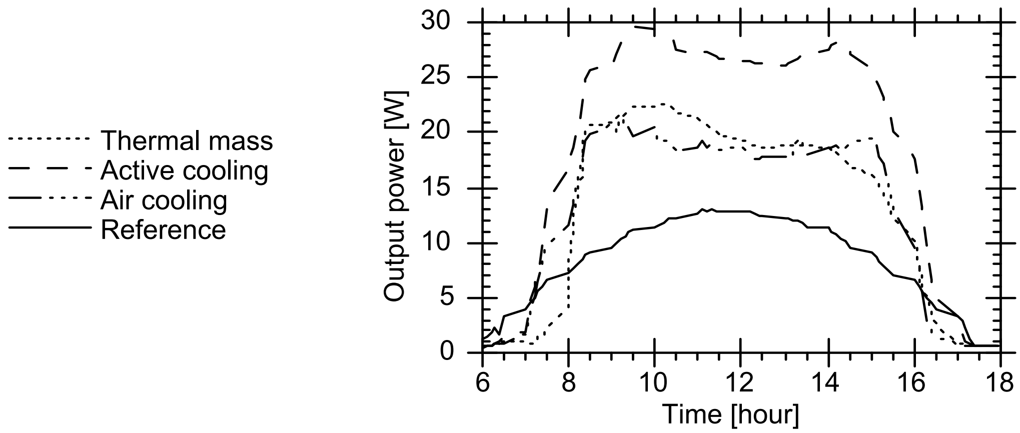


Figure 3. Example of output for some different concentrator modules during a clear day. Data from August 11, 1998.

It was concluded that the water content was too small in the concentrator module with a thermal mass since the temperature of the water was increased by 40°C during less than two hours during a day with full sunshine. However, if the thermal mass were 2-5 times larger, the temperature rise would be considerably slower, which would increase the output compared to that measured during clear days.

The module with air cooling cannot be essentiallyimproved. In a CPC the lower part of the reflector is most important for reflecting the radiation to the module, and cutting away a larger part of the reflector (for supporting larger air flow over the module) will markedly reduce the optical performance. The performance of the module with a cooling fin shows that there is a possibility of achieving rather low module temperatures with passive cooling. However, in this experiment a commercial cooling fin was used, and an economically better alternative would be to use the existing reflectors as cooling fins. Besides the saving of extra costs for a cooling fin with such a construction, the assembly of the module to the concentrator can be simplified.

4. Hybrid PV thermal systems

Active cooling of PV systems is interesting due to the possibility of co-generation of thermal and electrical energy. In the experiment performed, the mean temperature of the module was too low, about 19°C, to be of interest for solar heating application. However, with slightly higher temperatures, the heat can be of commercial interest, for example for pool heating, for low-temperature heating systems or for pre-heating of domestic hot water.
There are some important reasons why co-generation of electricity and thermal energy are of interest. Today, the cost of PV-produced electricity is very high, in the order of 0.50-1.50 $/kWh (Bevan 1997). This can be compared, for example, to 0.04--0.10 $/kWh for land based wind power in the same report. Away from the electricity grid this cost for PV electricity is still competitive in a large number of niche applications and is now approaching the range of small diesel generators, if costs for operation and fuel transport are included. This can lead to a large expansion of the PV market. But to reach levels that will influence the global energy balance, grid connected PV systems are required. Unfortunately the present PV technology is far too expensive to compete in the grid without heavy subsidies. Even if the PV modules are free the inevitable costs for design, installation, power management equipment, wiring, and support structure will only allow the costs to be roughly halved (Leng 1996). Most of this is due to the comparatively low net energy output per m2 of PV cell area. Radical technology changes are therefore needed to make PV cost effective in grid applications. With co-generation of heat and electricity, the total efficiency of the system will increase, and thereby the generation of heat can, to a larger or smaller extent contribute to the installation cost, giving better economy for the electrical fraction.

Another reason for co-generation is that there is an obvious risk that there may be rivalry about available surface in the future. Today several schemes for large building integrated PV installations are under discussion. In the European Community, 500 000 roof-integrated grid-connected systems should be installed before the year 2010. Similar large scale plans are discussed for Japan and USA. If these and other plans for building-integrated PV-systems will be realised, the systems may occupy a larger part of the available roof (or facade) and it may be difficult to find space for parallel solar thermal installations on these buildings, unless heat and electricity are produced simultaneously by the same installation.

The use of concentration devices, similar to those previously discussed, for co-generation of heat and electricity has important advantages. With concentration, the heat losses can be kept at a low level, which is important for high thermal efficiency. Although it can be assumed that PV module prices will fall in the future, concentrating devices reduce the module area and thus reduce the cost for PV modules. For efficient cooling of the PV modules it is also very important that there is a good thermal contact between the total module area and the cooling fluid, otherwise there may be ”islands” on the PV module with high local temperatures which destroy the overall effect of cooling. Efficient cooling of a module is simple if the module is small, and with reduced module area due to concentration, the piping cost for the thermal part of the equipment is reduced.

The experiments, which started by investigating different cooling techniques for PV modules equipped with concentrators, will continue with measurements on a hybrid PV thermal concentrating system during the summer of 1999. The geometry will be similar to that shown in figure 1, but with an anti-reflection glazing on top of the concentrator to protect the reflector and PV module and to reduce the heat losses. The modules will be cooled by water circulating in 10 mm aluminium plates tightly glued on the back of the modules, which is expected to give a homogenous temperature on the module area. The amount of electricity needed to circulate the cooling fluid is estimated to correspond to approximately 2 % of the annually produced electricity from the PV module (Karlsson et. al., 1998).

Figure 4 shows a simulation of the expected annual performance of such a system, based on Stockholm’s (lat. 59.4°N) climate. The module parameters used are C = 4X, $t_{glazing} = 0.9$ $r_{reflector} = 0.9$, $a_{absorber} = 0.9$, $U_L = 3$ [W m^2 K^{-1}]. The PV module efficiency is estimated to 10% at 1000 W irradiation and 25°C cell temperature. Although these parameters may be somewhat different in a real installation, the results indicate that there are good prospects for producing useful temperatures of the cooling fluid with only a slightly reduced performance of the electricital fraction of the PV/thermal hybrid system.

5. Conclusions

• Different methods of cooling PV modules equipped with CPC-reflectors were investigated. Table 1 and figure 2 show that the output from the actively cooled module is largest and the module with a cooling fin has the next best result. The output for the two modules with large thermal mass and air cooling is considerable lower.

• Hybrid PV/thermal systems are of interest for reducing the cost of PV generated electricity. To a large extent this has to do with the low efficiency of conventional PV systems, which implies large area-depending costs. For good performance it is important that there is a good thermal contact between the total module area and the cooling fluid.

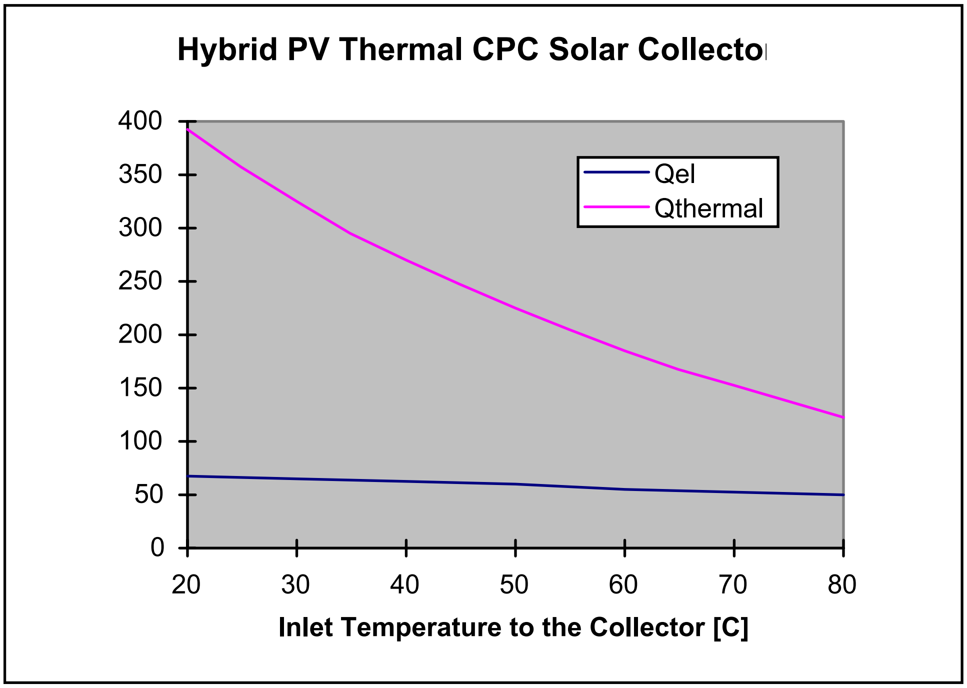


Figure 4. Expected output from a Hybrid PV/thermal solar collector. Collector parameters are defined in the text. Climatic data from Stockholm, lat. 59.4°N.

Acknowledgements

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

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