Performance evaluation of low concentrating photovoltaic/thermal systems: A case study from Sweden

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321 – Evaluation of a Parabolic Concentrating PVT System

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Abstract

The purpose of this study was testing and performance simulation of an innovative tracking hybrid solar system being developed by the Swedish Company *Arontis*. The *Solar8* collector produces both electrical and thermal energy in one system. Its performance was compared with conventional photovoltaic panels and solar thermal collectors working side-by-side which are already on the market. The *solar8* sample tested in Lund is a prototype designed for small demonstration projects and further development is ongoing.

The evaluation shows that the thermal collector has an overall heat loss coefficient of 3.1 W/(m^2.ºC), an optical efficiency of 65% and an electrical efficiency at 25ºC of 8% per active glazed area. If we account the total glazed area instead, the thermal collector has an overall heat loss coefficient of 2.5 W/(m^2.ºC), an optical efficiency of 52% and an electric efficiency at 25ºC of 6%. The electric efficiency of the bare cells is 16%. Annual performance simulations were carried out for the Swedish (Stockholm), Portuguese (Lisbon) and Zambian (Lusaka) climate. From the simulations one can conclude that: Solar8 can be replaced by a traditional PV-thermal collector side-by-side system using less space and producing the same electric and thermal outputs; tracking around one axis placed in North-South direction is considerably better then tracking around an axis set on East-West direction; the global irradiation on a static surface is always higher when compared with the beam irradiation towards a tracking concentrating surface; the ratio between electric and thermal output decreases when *Solar8* is moved to the equator.

Keywords: Solar8, Solar Hybrids, Photovoltaic Thermal Concentrators, PVT

1. Introduction

The overall problem with the use of PV-systems is the high cost of the solar cells. This makes it appealing to concentrate irradiation on the PV module in order to minimise the required PV-area for the same output. With increased light concentration, there will be a demand of increased cooling on the PV cells in order to lower the working temperature preventing damages and maintaining cell efficiency. Solar8 is a photovoltaic/thermal parabolic concentrating system that tracks and concentrates light into a water cooled photovoltaic module working as a thermal absorber. By using the heat generated in the absorber, the photovoltaic/thermal device (PVT) generates not only electrical, but also thermal energy (Fig. 1). The photovoltaic module is formed by two sections, each one with 32 cells. These sections can be connected both in series and parallel. Generally, a concentrating system with a large number of series connected cells like Solar8 is highly sensitive of local defects in the optical system and on the solar cells, supposed to receive an equal amount of irradiation. The total electric output is limited by the output coming from the poorest cell since all the cells are series connected. This is one of the challenges to overcome in this new technology. Local diodes installed in each cell can be able to bypass the current over the poorest cells and help reducing the problem with uneven radiation.

Fig. 1. Solar8 trough in Energy and Building Design Laboratory, Lund Technical University (LTH).

It is important to notice that the production of both heat and electricity is favoured by lowering the operating temperature. However a minimum water temperature is generally required by the given application involving higher working temperature on the cells. Due to lower insulation, the hybrid system thermal losses are higher when compared to a normal solar collector. Hence, it is expected that a flat plate hybrid system will deliver approximately 10% less electricity and 10% less heat compared to a thermal collector beside a PV module with the same cells amount [1]. It is also important to have in mind that when an electric load is connected to the PV cells, the thermal efficiency is further decreased since part of the radiation is converted into electricity.

3. Measurement results and system design

3.1. Electrical performance

During this study it was not possible to measure the cells temperature directly since the trough structure is closed. Hence, the average water temperature running inside the thermal absorber at the moment of the electrical efficiency measurement is presented instead. Using the maximum electric power extracted by *Solar8* together with the incident beam irradiation it was possible to estimate the electrical efficiency behaviour of the system depending on its working temperature (Fig. 2).

From the linear representations of the electrical performance it is possible to estimate that the electrical efficiency is 8.3% per active glazed area and 6.3% per total glazed area at 25ºC average water temperature running inside the thermal absorber. The slope of the electrical performance trend lines fits fairly close the classical 0.4% drop in efficiency per ºC in cells temperature increase. For this study, active area was defined as the maximum glazed area the system can make use of.

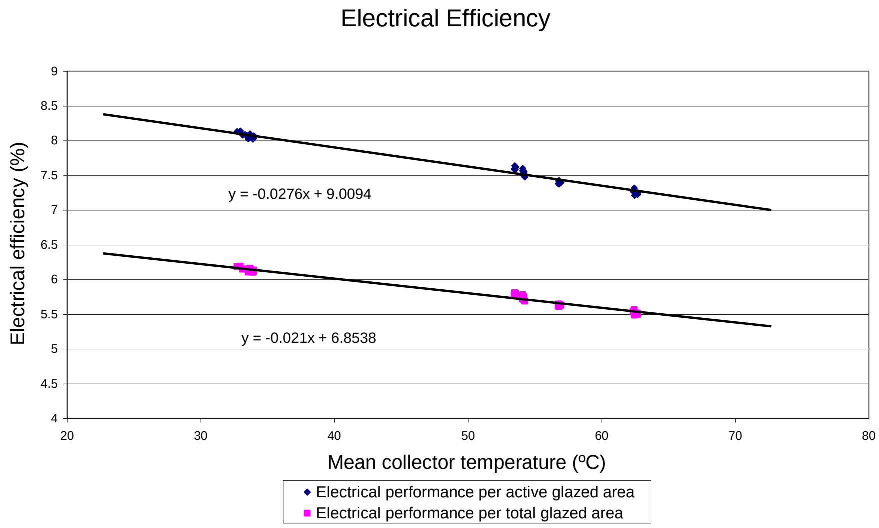

Fig. 2. Electrical efficiency calculated per active glazed area and total glazed area for different working temperatures. Linear adjustments representative of the electrical performance of the trough. ($A_{active\ elect.}$= 3.5m^2 A_{total}=4.6m^2).

3.2. Thermal performance

Using linear adjustments, the hybrid optical efficiency η_0(-) and the thermal losses coefficient U(W/m^{2o}C) were calculated. The thermal losses coefficient is the slope of the thermal efficiency estimated linear behaviour while the optical efficiency is the interception of that line with the yy axis (Fig. 3 and Table 1). The optical efficiency represents the thermal efficiency when there are no thermal losses since the ambient temperature is the same as the average temperature in the thermal receiver.

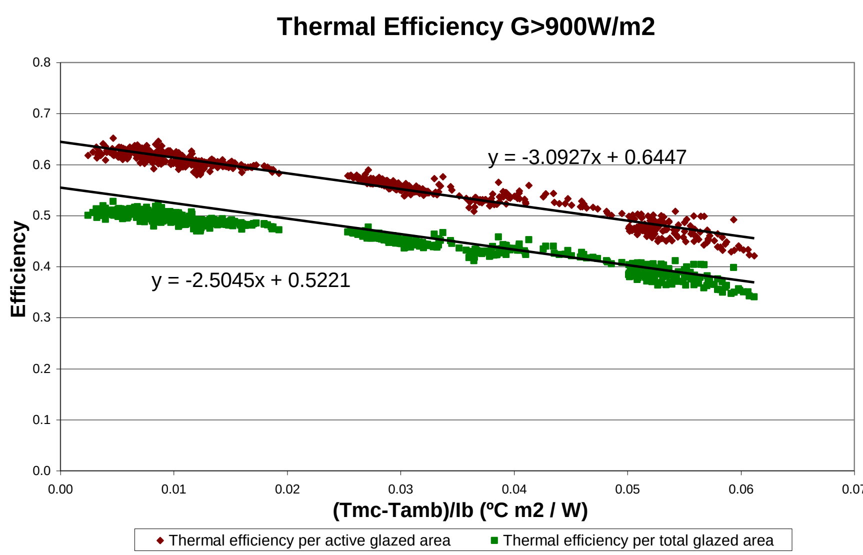

Fig. 3. Assumed linear thermal behaviour based on thermal efficiency measurements calculated per active glazed area and total glazed area. The efficiency was estimated based on measurements for global irradiation values higher than 900W/m^2. ($A_{active\ thermal}$=3.7m^2 A_{total}=4.6m^2)

Table 1. Measured optical efficiency η_0(-) and thermal losses coefficient U(W/m$_2$ºC).

Thermal parameters	Per active glazed area ($A_{active\ thermal}$=3.7m^2)	Per total glazed area (A_{total}=4.6m^2)
η_0(-)	0.64	0.52
U(W/m^{2o}C)	3.1	2.5

3.3. Electric and thermal output interaction

In Fig. 4, it is possible to comprehend the performance of a PVT hybrid system when it comes to thermal and electrical outputs interaction. As it is represented, when an electric load is connected to the electric circuit, electric power can be extracted. This means that part of the incoming irradiation is transformed into electricity by the PV cells instead of being absorbed by the thermal receiver. Hence, the thermal output decreases as much as the electrical output is extracted.

3.4. Reflector optical accuracy and design

Given that the measured system electrical efficiency (8.3% at 25ºC) is significantly lower when compared with the bare cells efficiency (16% at 25ºC), experiments were carried out in several components accuracy in order to estimate their influence in the final electric and thermal output breakdown. One of the most significant inaccuracies relates to the reflector. Ideally, every light beam perpendicularly incident to the glazed cover of the trough should be reflected to the PV module. Laser beam tests were carried out during the night and the glazed areas where the light was not focused on the PV cells were marked and are illustrated in Fig. 5. I-V curves were measured with and without the covers and the electrical output was roughly the same. The glazed marked area is approximately 15% of the total glazed area and can represent an optical efficiency margin of improvement on the reflector accuracy for future models. The system design still has a relevant margin of improvement on most of its components accuracy which makes it possible to achieve higher efficiencies in the future.

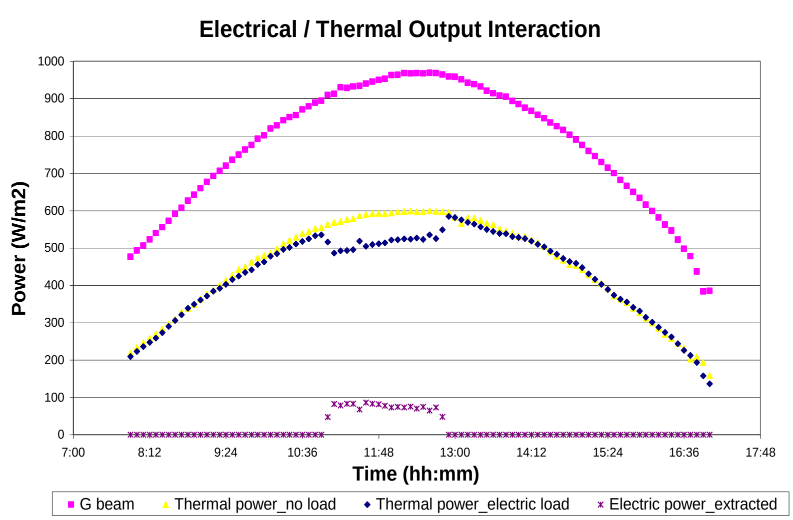

Fig. 4. *Solar8* electric and thermal outputs interaction per active glazed area measured along two clear days with and without electric load. ($A_{active\ thermal}$=3.7m^2 $A_{active\ elect.}$= 3.5m^2)

Fig. 5. Areas covered with paper where the incident light is not focused on the PV cells.

4. Simulation and calculation

4.1. Model and parameters

The model of the power outputs calculated in the performed simulations is described by the following equations and parameters [2].

$$P = \eta_{ob}K_{ta}G_b + \eta_{od}G_d - a_1((T_{out}+T_{in})/2-T_{amb}) - a_2((T_{out}+T_{in})/2-T_{amb})^2 \quad (1)$$

where $K_{ta} = 1-b_o(1/\cos\theta-1)$ (2)

$\eta_{od}=K_{diffuse}*\eta_{ob}$ (3)

Monitored parameters:

P	Power from collector (W/m^2)
G_b	Beam Irradiance (W/m^2)
G_d	Diffuse Irradiance (W/m^2)
T_{in}	Inlet temperature
T_{out}	Outlet temperature
T_{amb}	Ambient temperature

Glazed areas:

$A_{active\ elect.}$= 3.5m^2 *Solar8* electric active glazed area
$A_{active\ thermal}$= 3.7m^2 *Solar8* thermal active glazed area
$A_{Solar8.}$= 4.6m^2 *Solar8* total glazed area

Parameters in the collector model:

η_{ob} Beam efficiency
a_1 Heat loss factor [W/m^2 K]
a_2 Temperature dependence of heat loss factor [W/m^2 K^2]
$a=a_1+a_2*\Delta T$ (4)
K_{ta} Angle of incidence modifier for beam irradiance
b_o Angular coefficient
$K_{diffuse}$ Diffuse incident angle modifier
θ Angle of incidence onto the collector [º]

Simulation Parameters:

Table 2. Systems parameters introduced in the performed simulations with *Winsun* software.

Solar system	η_{0b} (-)	$K_{diffuse}$ (-)	a_1 (W/m^2 ºC)	a_2 (W/m^2 ºC^2)	b_0 (-)
Thermal *Solar8* per active glazed area	0.64	0.1	3.09	0	0.1
Electrical *Solar8* per active glazed area (50 ºC)	0.076	0.1	0	0	0.1
Flat plate collector (50 ºC)	0.8	0.9	3.5	0	0.1
PV module (25 ºC)	0.16	0.9	0	0	0.1

4.2. Sun tracking orientation

The *Solar8* system is mounted on our laboratorial facilities with its tracking axis oriented in the East-West position. It is possible to simulate the received irradiation by a tracking surface both with the axis in East-West and North-South direction for several climates at different latitudes. The results are given in Table 3.

By the analysis of the results, one can conclude that it is always better to track the sun around an axis with North-South direction. This effect is even more relevant when the system is moved closer to the equator where the sun reaches higher altitudes and moves around the sky from East to West direction, mostly.

Table 3. Incoming beam and global irradiation onto a tracking surface with axis in East-West and North-South direction for Stockholm, Lisbon and Lusaka.

Sun tracking orientation of the surface	Stockholm (lat=59.2ºN)		Lisbon (lat=38.7ºN)		Lusaka (lat=15.4ºS)	
	G (kWh/m^2,yr)	G_b (kWh/m^2,yr)	G (kWh/m^2,yr)	G_b (kWh/m^2,yr)	G (kWh/m^2,yr)	G_b (kWh/m^2,yr)
Tracking surface around North-South axis	1343.0	787.3	2187.0	1445.0	2594.0	1754.0
Tracking surface around East-West axis	1262.0	717.6	1973.0	1263.0	2289.0	1474.0
Ratio N-S/E-W tracking	1.06	1.10	1.11	1.14	1.13	1.19

4.3. Static surface vs. tracking concentrating surface

Another issue to take into account is that concentrating solar systems, with concentration ratio C=10, can make use only of the beam irradiation plus 10% of the diffuse one, roughly. On the contrary, non-concentrating systems make use of the global irradiation coming from the sun. Thus, the received global irradiation by a non-concentrating static surface was compared with the beam irradiation plus 10% of the diffuse onto a tracking concentrating surface (Table 4).

Table 4. Incident irradiation on a static non-concentrating surface and on a tracking concentrated surface. Static surface inclination from horizontal is 40º in Stockholm, 30º in Lisbon and 20º in Lusaka.

Static surface vs. tracking concentrating surface	Stockholm (lat=59.2ºN)	Lisbon (lat=38.7ºN)	Lusaka (lat=15.4ºS)
Static non-concentrating surface G (kWh/m^2,yr)	1170.0	1865.0	2164.0
North-South tracking concentrating surface Gb + 10%*G_{diff} (kWh/m^2,yr)	842.1	1518.2	1836.9
Ratio Static/Tracking concentrating surfaces output	1.39	1.23	1.18

The global irradiation incident on a static surface is higher when compared with the beam irradiation plus 10% of the diffuse towards a tracking concentrating surface. This means that a non-concentrating fixed collector receives more usable irradiation than a tracking concentrating one like *Solar8*. Closer to the equator, the beam irrradiation values are higher and this result becomes less accentuated.

4.3. Electric/Thermal power ratio in Solar8

Knowing that the beam fraction of the global irradiation increases when we move closer to the equator, conclusions can be taken on *Solar8* electrical/thermal output ratio depending on its location (Table 5).

Table 5. *Solar8* electric and thermal annual outputs per square meter of total glazed area, on a N-S tracking axis and 50ºC average working temperature. The total glazed are on *Solar8* is $4.6m^2$.

Solar8 annual outputs per glazed area (A_{Solar8}= 4.6 m^2)	Stockholm (lat=59.2ºN)	Lisbon (lat=38.7ºN)	Lusaka (lat=15.4ºS)
Solar8 electric annual output per glazed area (kWh/m^2,yr)	47.7	86.8	105.7
Solar8 thermal annual output per glazed area (kWh/m^2,yr)	159.7	434.9	605.3
Ratio Electric/Thermal	0.30	0.20	0.17

The ratio between electric and thermal outputs decreases when *Solar8* is moved closer to the equator where the beam irradiation values are higher. The electric output is proportional to the irradiation thus, a PV module as constant efficiency for the same working temperature. A solar collector as higher efficiencies for higher irradiances since the thermal output increases more than proportional when the irradiation increases.

4.4. *Solar8* vs. traditional side-by-side system based on glazed area

There are many ways and factors to take in account when comparing the performance of a concentrating hybrid with a traditional side-by-side system composed by a PV module and a solar collector working separately. The following tables feature *Solar8* comparison with the traditional side-by-side system based on their power outputs and total glazed area (Table 6 to Table 8).

Table 6. *Solar8* electric and thermal outputs with a N-S tracking axis at 50ºC average working temperature.

Solar8 annual outputs ($A_{\_Solar8}$= 4.6 m^2)	Stockholm (lat=59.2ºN)	Lisbon (lat=38.7ºN)	Lusaka (lat=15.4ºS)
Solar8 total electric annual output (kWh,yr)	219.2	399.0	486.1
Solar8 total thermal annual output (kWh,yr)	733.9	1998.9	2782.1

Table 7. Traditional side-by-side-system electric and thermal outputs per square meter of glazed area. The PV module η_{0b}=16% at 25ºC. The flat plate collector η_{0b}=80%, a_1=3.5 W/m^{2o}C and operates at 50^{o}C average working temperature.

Traditional side-by-side system	Stockholm (lat=59.2ºN) Fixed tilt=40º	Lisbon (lat=38.7ºN) Fixed tilt=30º	Lusaka (lat=15.4ºS) Fixed tilt=20º
PV module output per glazed area (kWh/m^2,yr)	173.2	278.7	324.5
Flat plate collector output per glazed area (kWh/m^2,yr)	478.7	999.7	1266.0
PV area needed to equal Solar8 electric annual output (m^2)	1.3	1.4	1.5
Collector area needed to equal Solar8 thermal annual output (m^2)	1.5	2.0	2.2

Table 8. Traditional side-by-side-system and *Solar8* comparison based on total glazed area.

Side-by-side system vs. Solar8 ($A_{\_Solar8}$=4.6m^2)	Stockholm (lat=59.2ºN) Fixed tilt=40º	Lisbon (lat=38.7ºN) Fixed tilt=30º	Lusaka (lat=15.4ºS) Fixed tilt=20º
PV module area / Solar8 total glazed area (%)	27.5	31.1	32.6
Thermal collector area / Solar8 total glazed area (%)	33.4	43.5	47.8
Side-by-side system area / Solar8 total glazed area (%)	60.9	74.6	80.4

The traditional side-by-side system uses less area than *Solar8* for the same electric and thermal outputs. This difference decreases when the systems are moved closer to the equator since *Solar8* is exposed to higher beam irradiation values. In Lisbon, for instance, *Solar8* can be replaced by 1.4m^2 of PV module and 2m^2 of thermal collector for the same outputs. Hence, it would use 74% of *Solar8* total glazed area (4.6m^2). Practically, two components require more space than one component.

4.5. *Solar8* vs. traditional PV module based on cells area

One of the most common arguments in favour of PVT concentrating systems is the higher electrical efficiency per cells area when compared with a regular PV module with the same cells area. In this situation and based only on the PV cells point of view, *Solar8* has a considerable higher efficiency per cell area when compared with the PV module (Table 9). This result can be explained by the higher irradiation the cells receive due to the reflector concentration factor and the tracking system. The thermal output can be seen just as an additional output one can get by cooling down the cells.

Table 9. *Solar8* and traditional PV module electric output comparison based on cells area. PV module inclination is 40º in Stockholm, 30º in Lisbon and 20º in Lusaka. A_{ceels}=0.33m^2.

Electric annual output per cells area (kWh/m^2)	Stockholm (lat=59.2ºN)	Lisbon (lat=38.7ºN)	Lusaka (lat=15.4ºS)
Solar8 tracking N-S (50ºC)	661.8	1204.7	1467.6
Traditional static PV module (25ºC)	192.4	309.7	360.6
Ratio Solar8/PV module	3.4	3.9	4.1

For this simulation it was considered that the PV module has16% efficiency at 25ºC, the same cells area as *Solar8* and that they cover 90% of its glazed area.
It is important to notice that the thermal and electric outputs shown previously don't take into account system distribution losses, array shading effects and load distribution.

5. Conclusions

With this study several conclusions can be taken not only for *Solar8* but also perhaps to the general photovoltaic/thermal concentrating hybrids being developed:

1. *Solar8* can be replaced by a traditional side-by-side system using less space and producing the same electric and thermal output.
2. Local diodes installed in each cell can be able to bypass the current over the poorest cells and help reducing the problem with uneven radiation.
3. One axis tracking around North-South direction is considerably better than tracking around an axis placed on East-West direction.
4. The global irradiation on a static surface is higher when compared with the beam irradiation towards a tracking concentrating surface.
5. The ratio between electric and thermal output decreases when *Solar8* is moved to the equator where the beam irradiation values are higher.
6. This PV/T combination still present lower outputs when compared with the traditional side-by-side system for the same glazed area. It is possible to say that there is chain efficiency around the most important components in *Solar8*. If every part of this chain works accurately and perfectly integrated in the system, higher efficiencies can be achieved in future models.

5. References

[1] Measurement report: Test of PVT module "PVtwin". IEA task 35. Danish Technological Institute.
[2] Duffie, J.A., & Beckman, W.A. (1980). Solar Engineering of Thermal Process. Wiley Interscience, New York.

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