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# Minimizing the Impact of Shading at Oblique Solar Angles in a Fully Enclosed Asymmetric Concentrating PVT Collector

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## Abstract

PVT collectors produce both electricity and heat from the same area. PVT collectors with low concentration factor allow both stationary and tracking configurations. For stationary or single axis tracking, the daily variation in the solar incidence angle can cause significant shading in concentrating collectors. Shading has a larger impact on PV than on thermal collectors and thus the evaluations was more focused on the electrical part. Several prototype versions of a novel design for a concentrating asymmetric PVT collector have been tested and compared. One tested improvement was replacing the reflective end gables with transparent end gables. Another improvement was to use different cell sizes. These actions were expected to minimize the impact of the shading at oblique solar incidence angles. The second action was found to be more beneficial than the first. Measurements were also performed in the solar simulator to fully understand the impact of shading in cell strings with 1/6 the size of standard cells. The latest version of the PVT was found to have, at 25°C and 1000w/m<sup>2</sup>, a collector efficiency of 13,7%, a cell area efficiency of 20,3% and an electrical power output of 237W. Lower side of the receiver was producing 58% of the total power.

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**Keywords:** Asymmetric CPC collector; PVT hybrid; shading; Transparent / Reflective end gables; Electrical Efficiency; Cell Size;

## 1. Introduction

Photovoltaic/thermal (PV/T) hybrid collectors produce both heat and electricity. The main benefits of PV/T collectors when compared to standard thermal and photovoltaic (PV) solar collectors are:

- The possibility to increase cell efficiency by reducing the cell operational temperature when the hot water is extracted at low temperatures. In a PV/T collector, it is very important that the receiver can transfer enough energy to cool down the cells efficiently and homogeneously.

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- The production of one unit of PV/T uses fewer raw materials than an equivalent area of thermal and photovoltaic panels. This is expected to enable a lower production cost per kWh of annual produced combined power [1].
- Reduction of the installation area, which enables the deployment of more installed capacity per roof area and may lower the installation costs.

Some PV/T manufacturers combine the PV/T concept with concentration to further reduce the usage of PV cells and thermal absorber material. Although concentration carries the penalty of extra reflection losses and lower Incident Angle Modifier (IAM) profile, it helps by reducing the amount of expensive components (solar cells, receiver and/or selective surface). Concentration also achieves higher temperatures, though higher temperatures will reduce the efficiency of the solar cells in PV/T collectors.

#### Nomenclature

CPC	Compound Parabolic Concentrators	PV	Photovoltaic
PV/T	Photovoltaic/thermal	I	Solar Radiation
P	Power	$\Delta T$	Temperature variation
U	Collector heat loss coefficient	$\eta$	Efficiency of a Thermal or PV panel
$\eta_0$	Maximum thermal efficiency for a given solar thermal collector	Imp	Maximum Power Point Current
Vmp	Maximum Power Point Voltage	Voc	Open Circuit Voltage
		Isc	Short Circuit Current

#### 1.1. The impact of shading in PV panels and solar thermal collectors

Shading has a considerably different impact on PV panels than on thermal collectors. In PV modules, the solar cells are often connected in series; thus one completely shaded solar cell will reduce the output of the whole string. Bypass diodes can be used to mitigate this effect by allowing current to flow in a different path at the expense of a minor fraction of the total power. However, the introduction of diodes increases both assembly time and material cost which lead to increased costs. On the other hand, diodes also prevent hotspots that can destroy PV panels. In thermal collectors, the decrease in power produced due to shading is approximately proportional to the shaded area. Thus, shading clearly has a much bigger impact on PV panels than thermal collectors.

In concentrating collectors, an additional aspect to consider is that non uniform concentration is considerably more critical for PV panels than for solar thermal. This is due to the fact that non uniform radiation in one cell increases the series resistance losses. Non uniform radiation intensity in a string with series connected cells has even a larger negative impact. Non-uniform concentration is present in all compound parabolic concentrators (CPC) [2]. The analyzed PV/T design is a CPC.

For these reasons, this study on shading was mainly focused on the electrical part of an asymmetric compound parabolic concentrating (CPC) photovoltaic/thermal hybrid (PV/T).

#### 1.2. The impact of the solar radiation in the efficiency of PV panels and Thermal solar collectors

The efficiency of a PV-system is almost independent of the solar irradiance, while on solar thermal-systems the efficiency is strongly dependent. The efficiency of a thermal collector is often zero at low light intensities. Figure 1 exemplifies the previous statement by showing the effect of solar radiation on both power and efficiency for PV panels and solar thermal collectors. Values were chosen in order to represent standard market panels. Thus the PV panel has an efficiency of 15% and the solar thermal collector has a maximum efficiency of 80%, and a total U value of 4 with  $\Delta T = (T_{med} - T_{ambient}) = 50^{\circ}C$  which was considered to be frequent. The graphics are drawn according to a simplified model using the

following formulas:

For PV panels:  $P = I * \eta$  (1)

$\eta = 15\%$  (2)

For solar thermal collectors:  $P = \eta_0 * I - U * \Delta T$  (3)

$\eta = P / I$  (4)

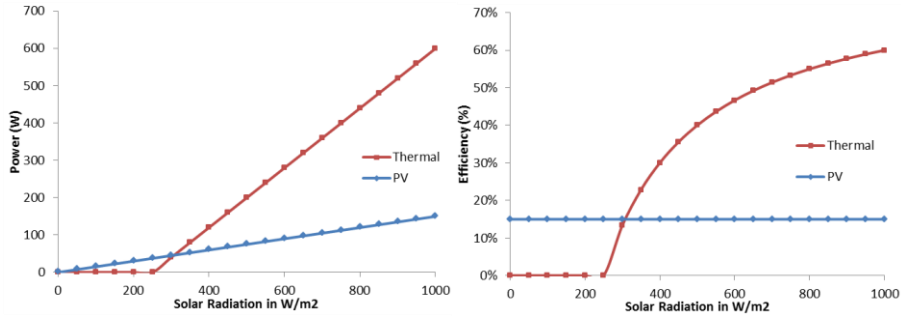


Fig. 1 - The effect of solar radiation in both the power and efficiency of both PV panels and solar thermal collectors

In this model, only the main factors are taken in consideration. In reality there are more factors to consider, such as the fact that the temperature of the solar cells will increase together with the solar radiation, which will lead to a decrease in solar cell efficiency. This means that the efficiency of the PV collector is not a straight line as shown but decreases with solar radiation following a coefficient of around 0,45%/°K for mono crystalline solar cells [3]. In the same manner, the PV power curve will continue to increase with solar radiation but the real curve is less steep than that shown above. However, the efficiency of solar cells is also increased for higher radiations which compensates for this effect.

## 2. Method

### 2.1. Description of the PV/T Design

Figure 2b shows the studied PV/T design, which is patented by Solarus, a Swedish company. The solar radiation is concentrated onto an aluminum thermal absorber. A highly transparent and electrically insulating silicone is used to laminate the PV cells to the thermal absorber on both the upper and lower sides of the absorber. The upper side works like a standard PV module without concentration, while the lower side receives the concentrated solar radiation from the compound reflector (parabolic and circular). The collector also has glazed protection and a supporting structure made of plastic and metal.

Though the concentration factor of the PV/T collector is a low 1.5, the PV cells can still reach high temperatures. Since mono-crystalline solar cells exhibit a reduction in power output at elevated temperatures [3], cooling maintains the electrical efficiency. Cooling is accomplished by running a fluid (normally water) through the channels of the thermal absorber. Thus the PV/T collector produces electricity and heat from the same area.

The optical axis for the reflector geometry is normal to the glass of the collector. This defines the acceptance angles; if the radiation falls outside this angle, the reflector does not redirect the incoming beam radiation to the lower side of the absorber and the optical efficiency of the collector is greatly reduced. The optics of the collector is further investigated in [4]. This way, the optical efficiency of the collector changes throughout the year depending on the projected solar altitude. The tilt of the collector determines the amount of total annual irradiation kept within the acceptance interval [5].

Figure 3 shows the water connections for extracting the heat (in blue) and the electrical arrangements of the solar cells (in red) in a PV/T collector, which has 2 troughs. Since both troughs are similar, most tests only investigated a single trough. The figure shows the collector plan view. The lower part of the receiver, i.e. the part that receives concentrated light, has exactly the same hydraulic and electrical configuration as the upper. The electrical part of each PV/T collector consists of eight parallel-connected strings, each with 38 series-connected cells. The total number of PV cells is 152 cells per trough.

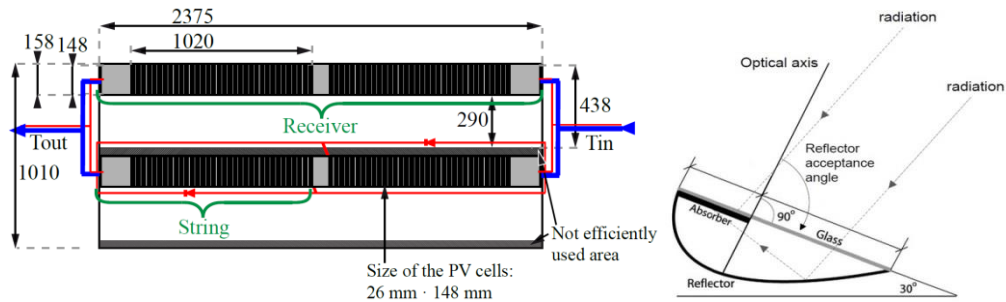


Figure 3. (a) Schematic view (from the top) of the PV/T hybrid collector, the water connection are drawn in blue and the electrical connections in red; (b) The geometry of the investigated PV/T hybrid solar collector

The solar collector manufacturer buys standard solar cells with 156mm by 156mm, which are laser cut into pieces of 26mm by 148mm. The objective is to increase the voltage and reduce the current at high irradiation levels and thus avoid any current capability constraints due to the increased concentration [1]. Figure 3 also shows the most relevant dimensions in the collector as the placement of the temperature sensors for the thermal tests. Active area (electrical or thermal) was defined as the area where the incident radiation can contribute to electricity or thermal production. For example, the electrical active area of a trough ( $0.865\text{m}^2$ ) is equal to the area of the cells of the upper side of the receiver ( $0.292\text{m}^2$ ) plus the area of the reflector in front of the cells, excluding edges, spaces between cells and parts where there was no reflector ( $0.573\text{m}^2$ ) [11]. In the same manner, active thermal area of one through was found to be  $1.017\text{m}^2$  while the collectors' total area is  $2,399\text{m}^2$ .

## 2.2. Properties of the materials used in the PV/T

The analyzed solar collector uses full square mono-crystalline solar cells from Big Sun Energy. These cells have an efficiency of 18,6% and a temperature dependence of  $0,43\%/^{\circ}\text{C}$  [6]. The reflector material is made of anodized aluminum with a total solar reflectance of 95% for solar thermal (measured according to norm ASTM891-87) and total light reflectance of 98% for PV (measured according to norm DIN 5036-3) [7]. The silicon that is used to laminate the solar cells has a transparency of 96% for PV and 93% for solar thermal [8]. The glass cover of the collector is made of low iron glass with solar transmittance of 95% according to the norm ISO9050 for solar thermal [9].

## 2.3. Experimental Setup

The different versions of the PVT collectors were tested in various locations in Sweden at different times, due to practical considerations, as shown in figure 4. Table 1 shows the equipment used at each of the locations. All locations have similar latitude and longitude. The indoor solar simulator consists of two rows of eight 1000W halogen light bulbs. The indoor solar laboratory was used for testing the shading impact on the strings using the Solarus custom-size cells.

Table 1. Overview of all measurement locations

Location	Solarus factory in Älvkarleby		Darlana University	Gävle University
	Indoor	Outdoor	Outdoor	Outdoor
<b>IV tracer</b>	Same for all measurements			
<b>Solar Radiation</b>	Reference Cell	Reference Cell	K&Z CM11	Reference Cell
<b>Temperature recording</b>	Not needed	LM35	PT100	Not available
<b>Flowmeter</b>	Not needed	Kamstrup 9EVL-MP115 flowmeter	Krohne Optiflux 5000	Not available
<b>Data Acquisition</b>	Not needed	MELACS	National instruments	Custom software

The IV Tracer is a custom made device, interfacing with the COM interface. A custom Excel macro logs the data periodically or on demand. The IV Tracer uses a current generator to measure the performance; it ramps up the current from zero to maximum, taking voltage and current samples in the process which lasts less than a second. Each I-V curve, with values of  $I_{mp}$ ,  $I_{sc}$ ,  $V_{mp}$ ,  $V_{oc}$ ,  $P_{max}$ , FF is saved as a separate CSV file. The device was found to have a resolution of 0.008V and 0.002A. In normal operation, an electric load is connected to the PV cells and electric power is continuously extracted at the maximum power point. However, the presented method of instantaneous I-V curve measurements simplifies the whole test procedure. These results are less expensive and less time consuming to achieve while still maintaining a good level of accuracy. If an electric load were continuously connected, the absorber would be colder since a part of the incoming radiation would be converted to electricity. This would mean lower temperatures and thus slightly lower thermal losses. This difference is small and has little impact on the results [5].



Figure 4. The outdoor measuring: (a) Solarus Factory PVT V1; (b) Darlana University PVT V2; (c) Gävle University PVT V3

The reference cell is from the European Standard Testing Institute and is calibrated to be linear from zero to 28.7mV at 1000W/m<sup>2</sup>. This reference cell had two outputs: one for data and one for temperature correction. The CM6 in Dalarna measured hemispherical irradiation with a total accuracy of 2% of the measured value. The CM11 measured diffuse irradiation and has an accuracy of ±1%. LM35 temperature

sensors were used for measuring the inlet and outlet temperatures in Älvkarleby, with a measurement range of  $-55^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$  and accuracy  $0.5^{\circ}\text{C}$  at  $25^{\circ}\text{C}$ . These were placed on the copper pipe directly outside of the collector and copper paste was used to ensure a good thermal connection. In Darlana, the sensors used were PT100s inserted inside the pipe, for water temperature, and in the shade for ambient temperature. These sensors have an accuracy of  $\pm 0.3^{\circ}\text{C}$  at  $0^{\circ}\text{C}$ . In Älvkarleby, the MELACS was used to log data. The MELACS (Micro Energy Logger And Control System) is a device built around a PIC16F micro controller. It was used as a standalone data logger to read data from thermal sensors and the reference cell. It accepts eight analogue voltage inputs in the range  $\pm 3.3\text{V}$  with a resolution of  $0.8\text{mV}$ . In Dalarna, data was logged via a National Instruments Data Acquisition Unit using LabView. A Kamstrup 9EVL-MP115 flowmeter was used in Älvkarleby, which sends 5760 pulses per litre flow, with precision varying from  $\pm 1.5\%$  at  $2^{\circ}\text{C}$  to  $\pm 0.5\%$  at  $120^{\circ}\text{C}$ . The Dalarna setup had Optiflux 5000 flowmeters from Krohne, which were accurate to  $\pm 0.1\%$  of the measured value.

#### 2.4. Differences between the tested PVT versions

In the effort for continuous improvement from the manufacturer, with emphasis to minimize the impact of longitudinal shading, several versions of the PVT collector were constructed and tested. The main differences relevant to this study are described below.



Figure 5. Differences between PVT V1 and PVT V2;

Table 2. Differences between the tested PVT versions

Version	PVT V1	PVT V2	PVT V3
<b>Collector Box</b>	Earlier version	Latest version	Latest version
<b>Receiver Type</b>	Non Massive Aluminium core	Massive Aluminium core	Massive Aluminium core
<b>End Gables</b>	Reflective	Transparent	Transparent
<b>Cell Size</b>	All cells were 1/6 of the size of a standard cells	All cells were 1/6 of the size of a standard cells	One trough with cell strings of 1/3, and the other trough with 1/6

**Collector Box:** The collector box has been improved from PVT V1 to PVT V2. The new collector box is sturdier and has improved water insulation. **Receiver Type:** The receiver design has been improved from PVT V1 to PVT V2. The V1 consisted of a number of parallel pipes of about 5mm diameter, laminated with two thin sheets of metal on either side while V2 is a massive aluminium extrusion with a patented cross-section. Manufacturer’s tests show that the new receiver design is more effective at cooling the solar cells and thus produces a very even heat distribution which reduces the  $F'$  value [1]. **End Gable:**

The end gable makes part of the box structure and its transmittance (or reflectance) properties are important for the collector performance. **Cell Size:** PVT V3 was specially built to evaluate the difference between collectors using standard cells cut into 1/3 and 1/6 of the original size. Strings with these types of cells were expected have different power performances over the day.

### 3. Results & Discussion

#### 3.1. Solar simulator testing - Shading of cell(s) in a string

Figure 6 shows the power reduction as well as the behavior of  $V_{mp}$ ,  $V_{oc}$ ,  $I_{mp}$  and  $I_{sc}$  during shading and that the shading greatly influences the intensity (A) but not the Voltage (V). Three types of shading were tested: whole string and single cell (parallel or perpendicular to the cell busbar). It is important to notice that the percentage of shading applied the cell or string is approximate.

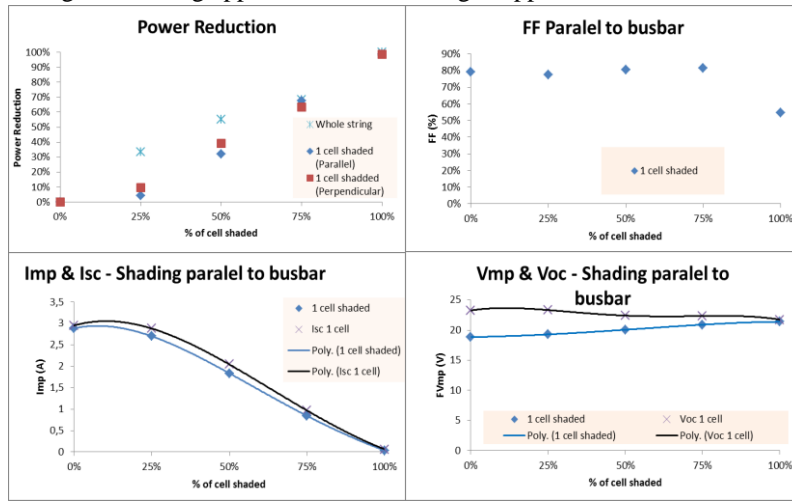


Figure 6. (a) Power Reduction; (b) Shading impact on FF; (c) Shading impact on  $V_{oc}$  &  $V_{mp}$ ; (d) Shading impact on  $I_{sc}$  &  $I_{mp}$

#### 3.2. Outdoor Testing

V1 was tested in Älvkarleby on the 1st of April and V2 at Darlana University on the 16th of May of 2013. Figure 7 shows the power output of one trough (both upper and lower sides of the receiver) for both V1 and V2 over stable sunny days. The collector tilt was selected to maximize output for the location and the time of the year in which the measurements took place. Cell temperature is assumed to be the same as the water temperature which, during the day, varied between 10 and 20°C for V1 and 20 and 40°C for V2. Figure 7 shows sharp increases and decreases of power output for both V1 and V2 due to the lower side of the receiver having one string (out of the two strings) not working. Since the cells are connected in series, as soon as the one cell becomes shaded, the power of the whole string is reduced. However, unshaded power production occurs only for little over 1h for V1 while in V2 it lasted for about 2h00. This is because V1 was an early prototype, so the cells strings were longer, causing the shading to begin earlier when compared to V2. The cell strings were longer as the spaces between each cell were larger. The peak power of V1 is 117W while V2 shows 89W. This difference is mainly justified by the difference in cell operating temperature and by the reflectance of snow in front of the collector. The findings for V1 verify the results from Bernardo et al [4] from 2012, made on a similar PVT prototype.

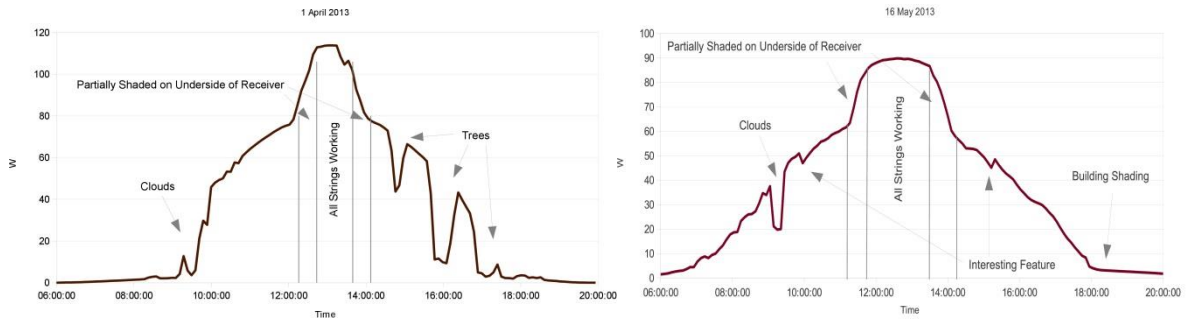


Figure 7. (a) Power PVT V1 measured in Älvkarleby; (b) Power PVT V2 measured at Darlana University

The power profile marked as “interesting feature” was seen to be caused by the combination of the movement of the shade caused by the aluminium frame and the shade caused by the end of the reflector. This was not visible in figure 7a, as V1 has reflective end gables, while V2 has transparent end gables.

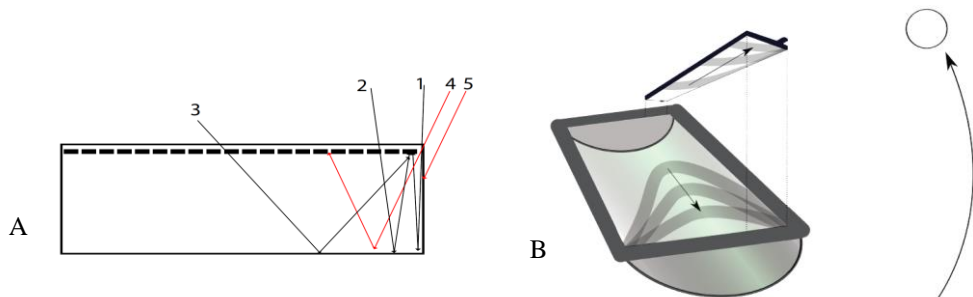


Figure 8 Effect of the shading of the aluminium frame on a PVT with: (a) reflective end gables; (b) transparent end gables;

This effect is further described in figures 8a and 8b which show how the shading caused by the aluminum frame varies over the day. The arrows show the movement of the shade produced by the frame on both the reflector trough and the reflector underside, as the sun moves from horizon to zenith.

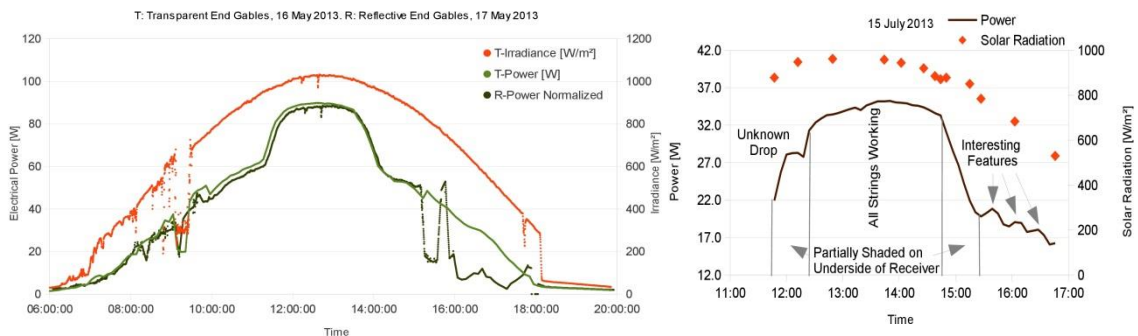


Figure 9. (a) Power output comparison between two V2s with transparent and reflective end gables; (b) Power output from the lower side of V3 (with 1/3 solar cells) measured at Gävle University on the 15<sup>th</sup> of July;

After full day of testing, a PVT V2 was modified and the transparent end gables were replaced by a reflective. The collector was then tested in the next day which was also a stable sunny day. This way, all collector properties were exactly the same and the only difference that is measured is the effect of the end



gable. For comparative purposes, the power output of V2 with reflective end gables was adjusted to the solar irradiation of V2 with transparent ones, as shown in figure 9a.

The figure 9b shows the power from the lower side of the experimental trough in the PVT V3. This trough contains strings with cells 1/3 of the standard size that was tested at Gävle University with perfectly stable solar conditions. Since there were no means to control the collector temperature at this location, the collector was kept fairly constant at stagnation (around 120°C). The time duration of no shading on the lower side was seen to be considerably longer than in V1 and V2, lasting more than 3h30. This happens because the strings with cells of 1/3 the standard size are shorter, since these strings have only half of the number of spaces between the cells.

Also for V3, the “interesting feature” is again seen due to the combination of the shading caused by the aluminium frame and the end of the reflector. These measurements were tested twice for confirmation.

Figure 10a shows the power on the lower side of both troughs of the PVT V3 on a day with perfect and stable solar conditions and collector temperature maintained at stagnation.

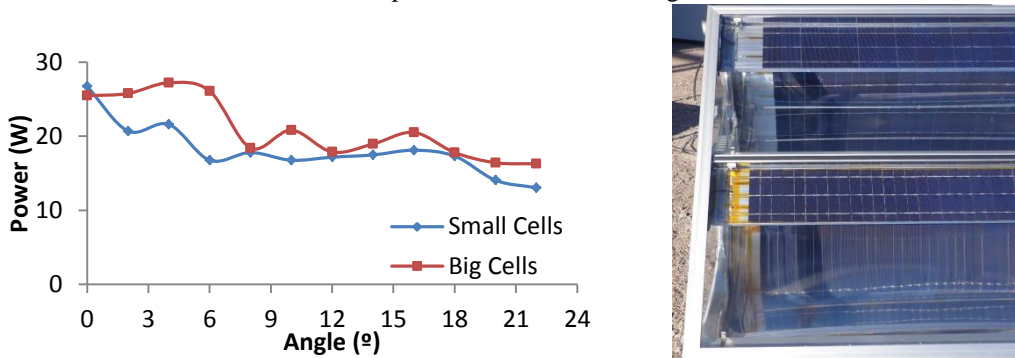


Figure 10. (a) Power output comparison between two V2s with transparent and reflective end gables; (b) Picture of PVT V3 showing a band of shading for the troughs with different cell sizes of V3

At (0,0) on the graph in figure 10a, two power readings were taken when neither of the troughs had any shading, but was about to start; at (0,0) the sun is not normal to the collector. The collector was rotated about 3° relative to the sun in order to provoke shading. For each angle, the two power readings were taken almost simultaneously from both troughs. This graph shows that when there is no shading, the trough with smaller cells produces more power, but the longitudinal shading also starts much before. The trough with larger cells produces more power even under shading since a larger part of the cell remains unshaded, as seen in figure 10b, which roughly corresponds to a 15° angle in figure 10a.

## 4. Conclusions & Recommendations

### 4.1. Indoor solar laboratory

The indoor solar laboratory tests showed that shading a cell parallel or perpendicular to the cell busbar had a similar impact in terms of power reduction. When 25% and 50% are covered, the power decrease is larger for the whole string than for a single cell shaded. The whole string experiences a power decrease close to the percentage of the area that is shaded while a single cell has a smaller decrease in power. Interestingly, having 75% of the whole string shaded or 75% of one solar cell resulted in a similar decrease in power. As expected, shading one whole cell or string yields a very similar result, with the power output very close to 0. The FF was observed to increase as the shading increased from 0% to 75%.

#### 4.2. Outdoors solar laboratories

For the latest PVT version, at 25°C and 1000W/m<sup>2</sup>, the collector efficiency was found to be 13,7% yielding 237W. The efficiency per cell area was found to be 20,3 %. At peak sun, the lower side of the receiver produced 58% of the total power in accordance with measurements done by Ricardo et al [4].

The testing on the three PVT versions showed clearly that the longitudinal shading caused by the frame is the main window of opportunity for improvement in this PVT design, in terms of power production optimization. The results also show clearly that the string length has a great impact on the duration of peak power with V1 having 1h, V2 having 2h and V3 having more than 3h30. The study shows that using cells with 1/3 the standard size gives better performance than smaller cells. Although larger cells show decrease in power production of 4% during peak power, peak power also lasts for a considerably longer period. Overall the net result will be a gain in power production over the day. Larger cells will also reduce the production costs by halving the work required. Further work includes investigating the extent of the benefits of using different cell types and sizes. Using cell strings with cells that are half the standard size and have four busbars instead of three is an option that should be evaluated.

To minimize the effects of longitudinal shading the authors recommend building the PVT collector with a transparent or much thinner frame. Reducing the frame shadow by half is expected to make a significant difference. Other measures like having less cells per string should also be evaluated. Alternatively, other reflectors geometries for the presented PVT concept can also be studied.

The receiver holder also creates a shade that is visible in the reflector. It is likely that this effect is not significant but this should be further as it can further increase the output of the PVT.

Although previous tests have unequivocally shown that transparent end gables perform better at large incidence angle than opaque, the results show no clear difference between having transparent or reflective end gable in the PVT. The difference may be within the measurement error. More testing is required for the larger incidence angles. With larger cells, the transparent end gables should perform better.

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