

Impact study of operating temperatures and cell layout under different concentration factors in a CPC-PV solar collector in combination with a vertical glass receiver composed by bifacial cells

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Abstract

Solar Collectors with Compound Parabolic Concentrator (CPC) reflectors redirect solar irradiance into the receiver (placed in optimal position). The concept of such devices is to reduce the installation area and energy costs. This research focuses on the behaviour and efficiency of a stationary CPC-PV solar collector. Each trough of this collector has different concentration factors (1.25 and 1.66) with vertically placed bi-facial cell receivers. An analysis of the electrical efficiency is performed in order to evaluate the viability of a CPC geometry with a vertical bifacial PV receiver. Furthermore, an investigation on bifacial cells performance due to concentration (and consequently increased cell temperature) is carried out. A numerical simulation of the yearly available radiation and the Incident Angle Modifiers (IAM) for each geometry is also conducted. Finally, a comparison between the simulations and the outdoor testing on the prototype collector is detailed. The tests took place in Gävle, Sweden (61° Latitude). The results showed that higher concentration factors led to larger operating temperatures (114°C for a concentration factor of 1.66 and 96°C for a concentration factor of 1.25). Although this may compromise the cell performance and shorten the device's life cycle, it is shown that appropriate ventilation will allow manageable operating temperatures.

Keywords: CPV, Photovoltaic, CPC, Bifacial Receiver, Monocrystalline Cells, Operating Temperatures, IAM, Cell Layout.

Technical Term	Symbol/Abbreviation	Unit
Concentrated Photovoltaics	CPV	-
Concentrating Photovoltaic and Thermal	CPVT	-
Compound Parabolic Concentrator	CPC	-
12 Full-Cell	12fc	-
24 Half-Cell	24hc	Adimensional
Computer-Aided Design	CAD	Adimensional
Concentration Factor	Cf	Adimensional
Fill Factor	FF	Adimensional
Incidence Angle Modifier	IAM	Adimensional
Incidence Angle Modifier - Longitudinal	IAML	Adimensional
Incidence Angle Modifier – Transversal	IAMT	Adimensional
Short Circuit current	I _{sc}	[A]
Current at maximum power point	I _{mp}	[A]
Rated P _{max} calculated with manufacturer's datasheet	R _{pmax}	[W]
Standard Test Conditions	STC	-
Maximum Power Voltage	V _{mp}	[V]
Open Circuit Voltage	V _{oc}	[V]
Yearly Collectable Energy	YCE	[kWh]
Angle between incident rays and collector's normal	θ	[°]
Acceptance Angle	θ_{accept}	[°]
Angle at which collector has maximum efficiency	θ_{def}	[°]
Angle between collector's normal and longitudinal plane	θ_L	[°]
Angle between collector's normal and transversal plane	θ_T	[°]

1. Introduction

A PV cell is designed to convert sun irradiation into electricity. Single crystal silicon cells present the best efficiency and represent 90% of the total PV applications (Salloom et al. 2018). Solar energy technologies, just like any energy technology, aim at providing energy at the lowest possible cost. With the usage of concentrators, PV modules can be developed in order to reduce energy costs and area consumption (Arnaout et al. 2016). Concentration has proven to be an effective alternative to more complex and expensive devices with tracking systems [6]. Renewable energy systems especially solar energy systems over the past 20 years became one of the main focal points in developing new technologies where energy can be produced with efficient results. The work presented in this study is based on the designing, building and testing of a CPC collector with bifacial solar cells. The following techniques and methods were employed: (1) the use of Computer-Assisted Design (CAD) software, (2) numerical ray-tracing simulations to predict power output (3) solar cell tabbing (manually soldering the bus wires or ribbons of each cell string) to build the PV receivers, (4) silicone lamination of the cells on top of high-transparency glass, (5) assembly of the prototype's wooden supportive frame and manual attachment of the reflective material, and (6) outdoor-testing. The main objective of this study is to understand the impact of different concentration factors in the device's performance, to determine the effect of temperature in the system output and to access the efficiency of different cell string versions (12 full-cells or 24 half-cells).

1.1. Concentrated Photovoltaics (CPV)

With 370 MWp globally installed in 2017, CPV is currently used as an option for utility-scale electricity generation, with sites already surpassing 30 MWp (Wiesenfarth et al. 2017). The principal aim of CPV is to potentially reduce the Levelised Cost of Electricity (LCOE), making it competitive to standard flat-plate PV in regions with high Direct Normal Irradiance (DNI), by using cost-effective concentrating optics that allow for a significative reduction in the cell area (Ju et al. 2017; Kost et al. 2013). DNI is defined as the amount of solar radiation per unit area of a surface normal to the incident rays. The cost-effectiveness of CPV technologies in areas with high DNI results from the effective concentration of direct sunlight by their optical components while achieving a poor performance with diffuse sunlight. CPV systems can be grouped according to their concentration ratios, from Very High Concentration PV to Low Concentration PV (LCPV) (Table 1) (Wiesenfarth et al. 2017; Kurtz, 2012).

Tab. 1: Types of Concentration Factors

Type	Concentration Ratio	Cell type
Low Concentration (LCPV)	2X-10X	c-Silicon or other cells
Medium Concentration (LCPV)	10X-100X	c-Silicon or other cells
High Concentration (HCPV)	100X-1000X	III-V multi-junction solar cells
Very High Concentration	>1000X	III-V multi-junction solar cells

Based on their optical configurations, CPV collectors can be differentiated whether the incident rays are concentrated into a focal line onto the absorber or receiver (e.g. parabolic troughs, Fresnel lenses) or into a focus point (e.g. parabolic dish, central receiver systems) (El-ladan et al. 2013).

CPV collectors can also be differentiated as non-imaging and imaging based on whether the image of the Sun is focused at the receiver or not. Belonging to the first category are compound parabolic concentrators (CPC) whereas all the other types belong to the imaging type. Non-imaging concentrators distribute the incident radiation from all parts of the solar disk onto all parts of the receiver without projecting on it clearly-defined images of the Sun (i.e. rays are not concentrated to a single point (Stine and Geyer, 2001). These collectors have low concentration ratios, generally below 10. In contrast, imaging concentrators form images (typically of low quality by common optical standards) on the receiver (Kurtz, 2012).

1.2. Compound Parabolic Concentrators (CPC)

The basic concept of the CPC is characterized by having a receiver placed between the focus of the symmetrical parabolas, a region known as the receiver opening, as to receive the concentrated radiation that is reflected from

them. The parabolas' optical axes define the lower and upper acceptance angles. Thereby, when light reaches the collector at an angle that is less than one-half of the acceptance angle, it will always reflect on the receiver. At incident angles greater than one-half of the acceptance angle, the light will be reflected out through the CPC's aperture without reaching the receiver. By using multiple internal reflections, CPCs are able of reflecting the entire incident radiation to the receiver as defined by the CPC's acceptance angle (Kalogirou, 2014; Sarbu and Sebarchievici, 2017). The diffuse radiation incident within the acceptance angles also contributes to the collector's output. Thus, by using a trough with two opposed parabolic sections (symmetric or asymmetric) facing each other, CPCs can accept great amounts of light, even without tracking systems. Provided the sun's apparent motion does not result in the incident solar irradiance falling outside the CPC's acceptance angle, the CPC's aperture need not be tracked since the sun's declination does not change more than the acceptance angle throughout a day (Stine and Geyer, 2001). When tracking is used, it can be very rough due to the concentration ratio being usually very low (Kalogirou, 2014). Tracking systems can lead to very high concentration ratios and will receive more solar radiation throughout the year than stationary collectors, although with the disadvantage of a more complex and costly installation (Giovinazzo et al. 2014).

The receiver can be configured in different ways: flat, bifacial, wedge, or cylindrical (Kalogirou, 2014). For a CPVT of the compound-parabolic type, the collectors are designed with a gap between the receiver and reflector to prevent the reflector from acting as a thermal bridge conducting heat away from the absorber. This is particularly important for flat absorbers. CPVT collectors are capable of providing greater thermal and electrical yields compared to stand-alone PV or hybrid PVT systems as incoming solar energy is maximized with the use of concentrators (Daneshezarian et al. 2018). In addition, as CPVT devices remove waste heat from the PV module, they can be more generally more energy-efficient than solar photovoltaics or solar thermal alone (Mojiri et al. 2013).

2. Methods

A computer simulation was performed to assess the behaviour and efficiency of the designed CPV. After the theoretical approach, results were compared with the output of the physical collector, as tested in outdoor conditions. The outdoor test allows a more detailed analysis after the general operating conditions of the CPV were assessed. Physical outdoor testing allows the understanding of variables such as clouds, wind, uneven irradiation distribution, temperature increase, ventilation, that are not considered in the computer simulation.

2.1. Collector Prototype

The prototype structural element is a pinewood skeleton with five ribs, 18-mm thick, which were laser-cut according to the concentrating geometry (Figure 1). The wooden skeleton hosts the reflective sheets, which are made from anodized aluminium with 93% optical reflectance (from manufacturer's datasheet. Almeco, 2019). Concentrating trough 1.25X (Fig. 1: point 3) with an aperture of 396 mm and 1.66X (Fig. 1: point 2) with 528 mm aperture. Side gables (Fig. 1: point 6) produced out of 4 mm Plexiglass sheets with optical transmittance of 86%, allow the support of the receivers (Fig. 1: point 4 and 5). Each PV bifacial cell receiver with a different cell layout is composed of low-iron supportive glass and silicone protection (96% optical transmittance for the silicone, according to manufacturer's specifications. CHT, 2019), 24 full cell version (Fig. 1: point 4) and 12 full cell version (Fig. 1: point 5). Both receivers are placed vertically in the middle of each trough. With the simple and modular design, the receivers can easily be switched between troughs during the outdoor testing. Finally, for water and dust protection, a Solar Glass cover with optical transmittance of 95% is assembled to the collector (Fig. 1: point 7).

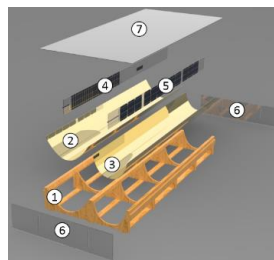


Fig. 1: Collector's exploded view.

2.1.1. Collector's bi-facial PV receiver

The full-sized mono c-Si bifacial cell has the same dimensions of a standard solar cell (i.e. 156 mm x 156 mm with chamfered edges of 15.4 mm). According to the manufacturer, the cell's nominal efficiency is 19.6% and its back factor (i.e. rear side nominal efficiency divided by front side nominal efficiency) is taken as 90%. Figure 2 shows the full-sized bifacial cell used as well as the half-cell and one-quarter cell types, all of them with three busbars, along with their nominal characteristics at STC.

Direction	Front
Efficiency (%)	19.60
P_{mp} (W)	4.69
V_{mp} (V)	0.53
I_{mp} (A)	8.87
V_{oc} (V)	0.63
I_{sc} (A)	9.38

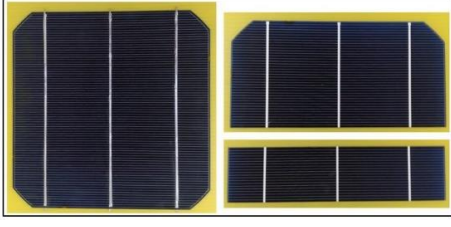


Fig. 2: Left side: Nominal characteristics of a full bifacial cell. Right side: Types of cut cells: full cell, half-cell and quarter-cell.

The bifacial strings are supported by a 4-mm thick low-iron glass with 95% solar transmittance. Initially, the cells were manually soldered and tabbed in series-connected strings, as shown in Figure 3. Then, to provide physical protection and electrical insulation, the backside of each string is laid down onto the supportive glass while the front side gets laminated within a 4-mm thick silicone layer with 96% light transmittance (CHT, 2019).



Fig. 3: Soldering of the bifacial-cell strings for the receivers.

2.2. Ray-tracing simulation methodology

2.2.1. Ray-tracing software

The theoretical output of the CPC-PV was simulated using open-source ray-tracing software (Tonatiuh) based on Monte Carlo analysis. This software was developed to assist in the design and analysis of solar concentrating systems with relevant features such as a robust theoretical foundation and computational scheme and clean and flexible software architecture (Blanco et al. 2005). The CAD model of the CPC is imported into Tonatiuh and the respective optical properties are allocated to each of its components, following manufacturer's specifications for the actual materials: anodized aluminium reflectors (93% reflectance. From Almeco, 2019), glass top cover (95% solar transmittance with a refractive index of 1.54), plexiglass side gables (86% solar transmittance with a refractive index of 1.492).

During the simulations, the sun shape follows a pillbox distribution as the solar intensity is constant for all points of the solar disk (Giovinazzo et al. 2014; Bader and Steinfeld, 2010). The irradiance is always set at 1000 W/m², and weather effects are disregarded. Automated script-based iterations calculate the incident radiation on the receiver for a full year with 1-hour intervals and accuracy of 10000 rays. It is important to highlight that the electrical output of the device is not calculated by the software, but rather the total incident power from the photons reaching the receiver. Thus, meteorological conditions, cell efficiency or degradation, wire resistance, optical transmittances and other factors affecting the actual electrical output are not considered during this simulation.

2.2.2. Incidence Angle Modifier

Incidence Angle Modifier (IAM) is known as the variance in output performance of a solar collector as the angle of the sun changes in relation to the surface of the collector, with respect to irradiance under normal incidence (Hertel et al. 2015). Both transversal (IAM_T) and longitudinal (IAM_L) planes were used for IAM's calculation, with increments of 10° . For IAM_T , the sun is initially positioned due north (long: 0° , trans: -90°) (see Figure 4 for reference). It is then moved due south along the transversal plane to an angle of (long: 0° , trans: 90°) with increments of 10° . The IAM for the longitudinal plane (IAM_L) is obtained by placing the sun due East (long: -90° , trans: 0°) with increments of 10° . At each increment, Tonatiuh runs one iteration of the ray-tracing simulation and calculates the incident irradiation on both sides of the receiver.

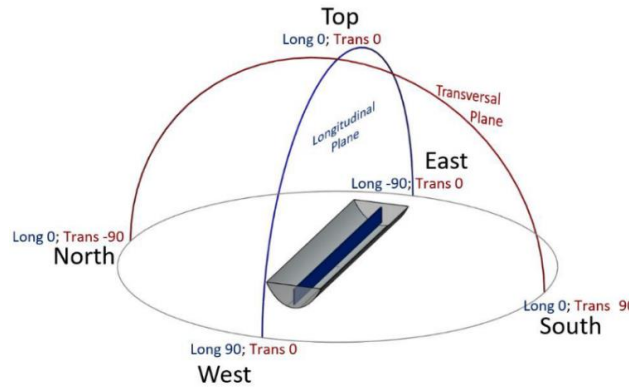


Fig. 4: Transversal (red) and Longitudinal (blue) IAMs measured with Tonatiuh.

2.3. Data acquisition

The receivers' peak power, i.e. output power at normal incidence, is measured under 1X and under the concentrations provided by the reflectors. When measuring under 1X, the receivers' IV curves are also obtained to determine their electrical performance and built quality. Similarly, the collector's power output dependence with varying sunlight incidence angles (incidence angle modifiers) is tested. The data is acquired outdoors from a rooftop installation located on the facilities of the University of Gävle, Sweden (60.6° N, 17.1° E).

2.3.1. Equipment

- i. An IV tracer typically generates a current that is ramped-up from zero to the maximum while voltage (V_{mp} and V_{oc}) and current (I_{mp} and I_{sc}) samples are taken during the process. The device used for measurements has a resolution of 0.008 V and 0.002 A.
- ii. The data logger CR 1000 from Campbell Scientific controls the acquisition and records the measured electrical data, including the values provided from the IV tracer. The data logger acquires the following IV characteristics: open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), power at maximum power point (P_{mp}), the voltage at maximum power point (V_{mp}), current at maximum power point (I_{mp}), fill factor (FF). Each IV curve is comprised of a hundred points recorded every 30 seconds. Also, both global and diffuse irradiance is measured by two pyranometers CMP6 and CMP3 model from Kipp & Zonen (Figure 5), respectively with 30-second sampling intervals.

2.3.2. Peak power testing

To determine the maximum power output under 1X concentration, the receivers are placed outside the collector's box while pointing their front face to the sun as to test for normal incidence. When testing for the output of a single face of the PV string, the opposite face is covered. In this way, the recorded power will be exclusively a product of the uncovered face (Figure 5, left side). The sun's position is tracked by considering its elevation and azimuth during the measuring process. To determine the maximum output at 1.25X and 1.66X, the receivers are then vertically-placed into each trough of the collector's box (each receiver switched to the other through after a set of measurements was performed) as the entire device is pointed normal to the sun position (Figure 5, right side).



Fig. 5: Left side: testing receiver output outside the collector at 1X concentration. In this case, the receiver back face is covered as to test for the peak power contribution, mostly from DNI, of the front face. Right side: The receivers are placed inside the box and switched between the two concentration troughs to test for their output at 1.25X and 1.66X.

2.3.3. Incidence Angle Modifiers

This section presents the results obtained for the transversal and longitudinal radiation IAM. Incidence Angle Modifier (IAM) is known as the variance in output performance of a solar collector as the angle of the sun changes in relation to the surface of the collector, with respect to irradiance under normal incidence (Cabral et al. 2017).

IAMs were measured outdoors in order to characterize the angular dependence in the collector's electrical performance. The transversal IAM (IAM_T) was measured by changing the tilt of the collector over the transversal plane while maintaining a fixed orientation towards the solar azimuth, while the IAM_L was obtained by changing the collector' solar azimuthal angle over the longitudinal plane while maintaining a constant tilt.

2.3.4. Solar cell temperature

To determine the effect of increasing temperature on the solar cells, a Type-K thermocouple is attached to a silicone-laminated bifacial reference cell on two separate receivers to replicate the working conditions of the tested PV receivers (Figure 6, left side). Temperature values were recorded by a thermocouple data logger Pico Technology© TC-08 Model® (Figure 6, right side). The thermocouples are often the preferred technique for solar cell temperature measurement over other techniques such as IR thermometers and thermal imaging cameras (Rolley et al. 2017). By using an isolated reference cell, the electrical output from the tested bifacial string is not affected by shading due to the thermocouple's mechanical attachment.

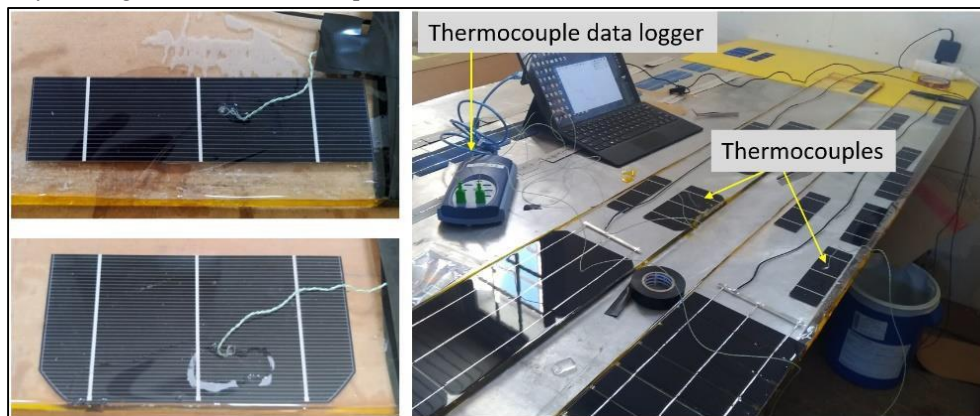


Fig. 6: Left side: K-type thermocouples attached to reference bifacial cells. Right side: thermocouple readings are recorded by a data logger from Pico Technology© connected to a portable computer.

The measurement of temperature on the bifacial cells was performed outdoors for both concentrations by inserting the two laminated reference cells into each of the collector's troughs while facing it normal to the sun position (i.e. normal incidence). As depicted in Figure 7, the temperature was measured on two different conditions: with an "open" collector (the collector's glass cover is detached), with a "closed" collector (the collector's glass cover is attached).

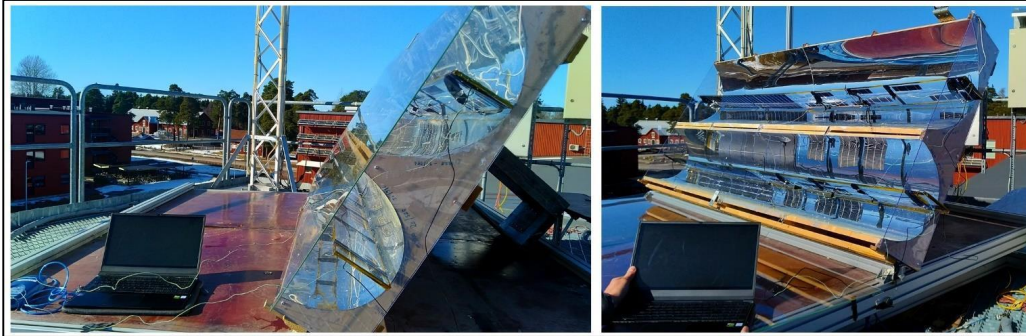


Fig. 7: Cell temperature was measured over two different conditions: with an "open" collector (Right) and with a "closed" collector (left).

3. Results

3.1. Ray-tracing simulations

3.1.1. Yearly simulation

Figure 8 shows the yearly simulations performed for the concentration factors of 1.25 and 1.66 with different tilt angles.

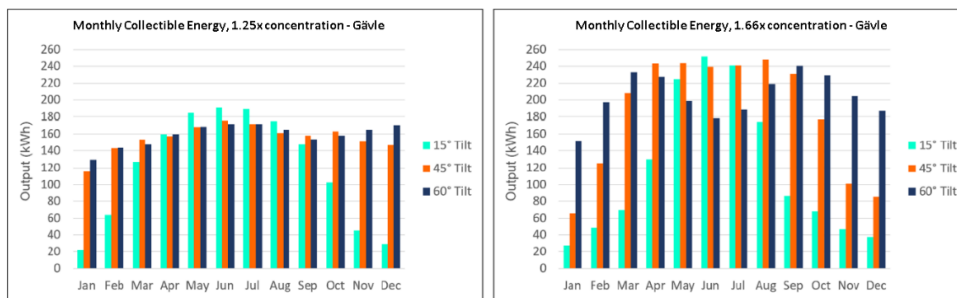


Fig. 8: Monthly Collectible Energy (MCE) for 1.25X and 1.66X for a tilt of 15°, 45° and 60° for Gävle, Sweden.

It is possible to conclude that the lowest tilt angle (15°) provides the maximum collectable energy during Summer months (May to August), peaking in June. This follows the asymmetrical irradiation profile at high latitudes. However, using the 15° angle, during the non-summer period, an abrupt drop in MCE is visible (values as low as 22kWh (1.25X) and 28 kWh (1.66X) in January). MCE is improved during the non-summer months when the tilt angle is increased. It is visible a less abrupt drop in winter and a more even profile along the year for MCE at higher tilts. 1.25X concentration geometry is a good example with a difference of only 60 kWh (at 45° tilt) and 42 kWh (at 60° tilt) between the worst winter month of January and the peak summer month of June. For both concentration factors the highest tilt yields the highest amount of yearly collectable energy, with 2456 kWh available for collection at 60° and 1.66X and 1905 kWh at 1.25X.

3.1.2. Simulation of Incidence Angle Modifiers

Figure 9 shows the results for the simulated IAM_T and IAM_L for both concentration factors of 1.25 and 1.66. Both curves are symmetrical, as expected. The version 1.66X has a more steep decrease in the IAM_T due to the bigger aperture of the collector, leading to a loss of power sooner than the version 1.25X.

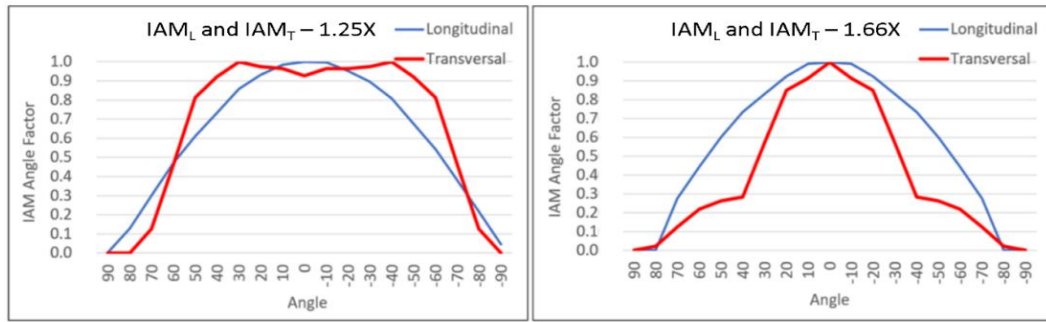


Fig. 9: IAM_L and IAM_T for a concentration factor of 1.25 (left side) and 1.66 (right side).

3.2. Outdoor testing results and analysis

3.2.1. Peak Power Testing

To determine Peak Power Output, 4 cases were studied. Each receiver IV curve was determined outside the box (1X) to investigate electrical performance and build quality (Figure 10). This study allows the assessment of the contribution to the total output of direct irradiance (front face) and diffuse irradiance (back face).

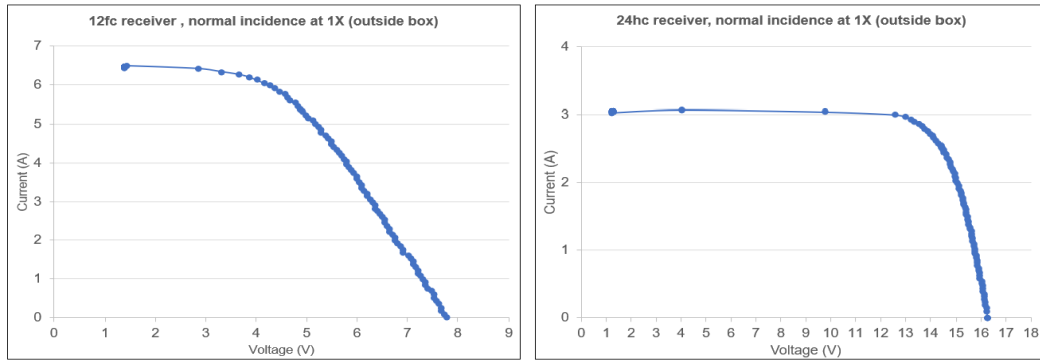


Fig. 10: IV traces at normal incidence for both receivers (no concentration applied).

The resultant shape of the IV curve “knee” relates to the receiver’s high series resistance probably due to micro-cracks induced from the process of manual soldering (Nguyen, 2010). 12fc version shows a fill factor of 52%, probably a consequence of construction imperfections causing a low efficiency and lower output than the 24hc version. On the other hand, the IV trace presents a fill factor of 78% for the 24hc receiver, resulting from better construction quality. Furthermore, the receivers were also tested in the collector’s troughs to measure the performance at 1.25X and 1.66X. The normalized P_{max} (N_{pmax}) data acquired by the IV tracer was calculated by normalizing P_{max} to an irradiance of 1000 W/m^2 . The rated P_{max} or R_{pmax} at 1X is calculated through the rated P_{mp} of the full-size bifacial cell from the manufacturer’s STC testing at 1X concentration.

- Receivers outside the box and only direct radiation on the front face (i.e. backside covered): 56W.
- Receivers outside the box, front face towards the sun subject to DNI and backface subject to diffuse irradiance. A backside factor of 90% is used and a factor for diffuse light of 10% is assumed (Kelly and Gibson, 2011): 61W.
- Receivers with both faces subject to 1X. Backside factor of 90%: 107W.
- R_{pmax} at C_f is calculated over the rated power at STC and adjusted to both concentration factors of 1.25 and 1.66: 134W.
- Receivers inside the box and both faces subject to both 1.25X and 1.66X. Backside factor of 90%: 178W.

The ratios $\frac{N_{pmax}}{1R_{pmax@1X}}$ and $\frac{N_{pmax}}{1R_{pmax@1Cf}}$ were determined to assess the efficiency of the collector by comparing the measured normalised output with the expected output at STC from the manufacturer’s rated specifications (Table 2).

Tab. 2: Results obtained after measuring outdoors the peak power (i.e. power output at normal incidence) from the receivers at different concentrations.

Receiver Type	N° of cells	Case	Total Cell Area (m ²)	Avg Global Irradiance @ collector's plane (W/m ²)	I _{mp} (A)	P _{max} (W)	Normalised P _{max} - N _{pmax}	Rated P _{max} - R _{pmax} @ 1X	Rated P _{max} - R _{pmax} @ C _f	N _{pmax} / R _{pmax} @ 1X	N _{pmax} / R _{pmax} @ C _f
12fc	12	Outside box	0.024	607	5.50	26	43	61	-	0.70	-
		Back covered, Outside box	0.024	619	5.38	24	39	56	-	0.70	-
		Inside box 1.66X	0.024	396	8.00	36	86	107	178	0.80	0.48
		Inside box 1.25X	0.024	392	4.60	28	51	107	134	0.48	0.38
24hc	24	Outside box	0.012	609	3.07	39	64	61	-	1.04	-
		Back covered, Outside box	0.012	595	2.91	36	61	56	-	1.08	-
		Inside box 1.66X	0.012	573	5.20	56	95	107	178	0.89	0.53
		Inside box 1.25X	0.012	360	2.00	23	69	107	134	0.64	0.51

The N_{pmax} at normal incidence for the 24hc receiver is calculated at 69W and 95W for the 1.25X and 1.66X concentration factors, respectively. These values have been 47% lower than the maximum power that could be delivered by the receivers according to the cell's nominal specifications, showing that the cells cannot handle the heat. a possible explanation raises from the inability of the tabbed metal ribbons to properly handle the amount of current generated from the bifacial cells subject to concentration, thus lowering the output power. As opposed to other CPC devices with bifacial receivers made from standard monofacial strings, the tested CPC prototype carries the current produced from both sides through a single ribbon connection. Furthermore, CPC design concepts typically use horizontal receivers where concentration occurs on just the bottom side.

Regarding overall efficiencies of around 14.6% for the 12fc receiver and 21.8% for the 24hc receiver, which are in line with the values presented for the worst fill factor (52%) measured for 12fc.

For the 24hc receiver, the 1.66X and 1.25X troughs show a ratio $N_{pmax}R_{pmax}@1X$ of 0.89 for the former and 0.64 for the latter. For the 12fc receiver, the ratio $N_{pmax}R_{pmax}@1X$ is 0.80 (1.66X trough) and 0.48 (1.25X trough). Clearly, on efficient collectors this ratio should have been closer to the concentration factors of 1.66 and 1.25, respectively. The fact the obtained values are about one half the ideal values on both receivers is evidence that nearly half the maximum theoretical power that could be delivered by the collector is lost. Even after considering optical effects, these results indicate a considerable inefficiency. A possible explanation arises from the inability of the tabbed metal ribbons to properly handle the amount of current generated from the bifacial cells subject to concentration.

3.2.2. Incidence Angle Modifier

IAM_L and IAM_T are obtained from the ratio between the outputs at each angle, divided by the maximum output (output at an optimal angle). Figures 11 and 12 show both transversal and longitudinal IAM (normalized for normal incidence at 1000 W/m²) for each reflector geometry and the respective type of bifacial receiver employed. Figure 11 shows the normalized longitudinal and transversal IAMs for full and half size PV cells, laminated into the solar glass receiver, for the CPC design with concentration factor of 1.66 and arc angle of 20°. Figure 12 corresponds to the CPC design of 1.25X with arc angle of 30°.

In terms of the overall trend of the curves, the measured IAMs (both transversal and longitudinal) show a reasonable correspondence with those simulated by ray-tracing methods. The geometries can redirect efficiently the sunrays towards the receiver when the angles of incidence through both concentration apertures are smaller than the half-acceptance angle. In all cases, the IAM curve of the 24hc receiver is below the 12fc receiver. This suggests that the half-cell layout is slightly more susceptible (5-10%) to lose power as the incident angle changes from optimal. This difference might be attributed to the change in the cell layout between the two receivers. For instance, the half-cell string layout had to be designed with double the amount of inter-cell gaps as there are double the amount of half cells than full cells.

The low fill factor of the full-cell receiver (12fc receiver) does not exclude it from providing sensible IAM results, as these are relative measurements which are normalised to the maximum output at optimal incidence, rather than absolute measurements. It is worth mentioning that the IAM_T curve for the 12fc receiver at 1.25X shows a large gap between 0° and 45° as the data points for 15°C and 30°C are missing. This issue, product of a measuring equipment problem, could not be addressed on time to be corrected in this report. Nevertheless, it presents a more steady decrease while the incidence angle increases (lower solar altitudes), which leads to lower cell stress, thus increasing the lifetime of the cells.

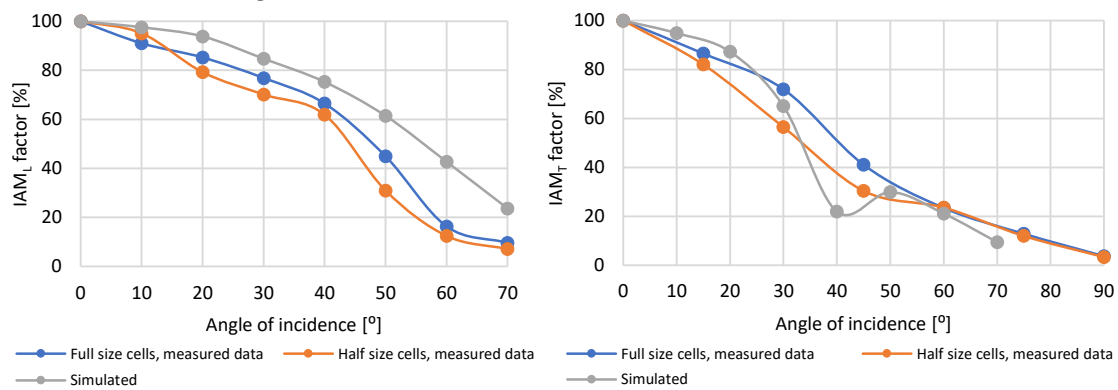


Fig. 11: Longitudinal (left figure) and transversal (right figure) IAM for a glass receiver composed by full and half-size bifacial solar cells, for a concentration factor of 1.66 and an arc angle of 20° .

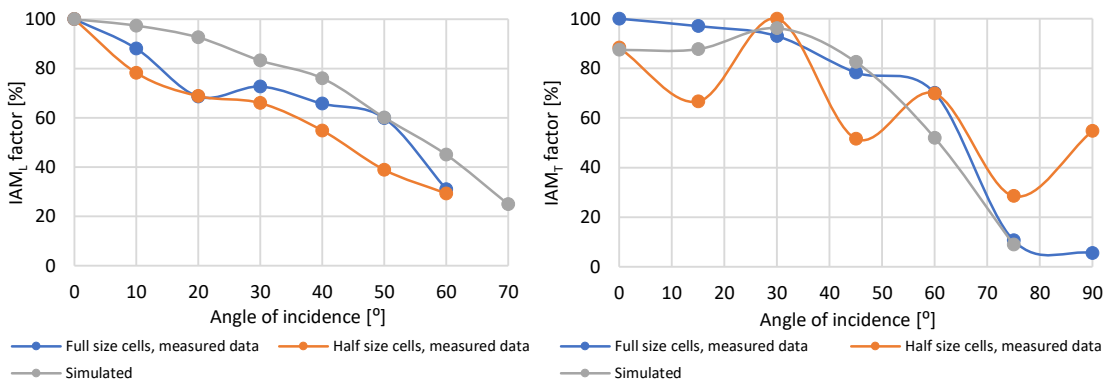


Fig. 12: Longitudinal (left figure) and transversal (right figure) IAM for a glass receiver composed by full and half-size bifacial solar cells, for a concentration factor of 1.25 and an arc angle of 30° .

3.2.3. Impact of Solar cell temperature

A parallel study has been performed to address the temperature in this type of concentrating solar collectors. Two cases were studied, (1) an open collector (without top glass cover) and (2) a closed collector with top glass cover. The graphs in Figure 13 show the correspondent temperature measurements for both cases (1) and (2). For case (1), the temperature tends to stabilize after a ~ 30 minutes of testing, staying within a fluctuating range of 33°C to 37°C (for the 1.66X, 47% of the maximum temperature reported by Lança et al. 2018) and from 24°C to 27°C (1.25X) during a period of around 30 minutes. However, a low-rate incremental trend of temperature persists for both concentrations. The temperature fluctuations are attributed to the cooling effect from the high speed of wind gusts experienced on the testing days. The temperature difference between the two concentrations is of around 8°C on average. On the other hand, for case (2) maximum temperatures of 114°C (76% of the

maximum temperature reported by Lança et al. 2018) and 96°C are reached by the reference cell at 1.66X and 1.25X, respectively. The difference in the climatological and irradiance conditions might be a factor in lowering the temperature as measured on the CPC prototype relative to the CFD simulations presented by Lança et al. (2018).

The last 24 minutes of measuring, the 1.66X curve shows 10°C of linear temperature increase (from 104°C to 114°C) which represents a rate of 0.42°C/min. For the 1.25X curve, there is only 2.89°C of linear temperature increase during the same 24-minute period (from 93°C to 96°C), corresponding to a much smaller rate of 0.12°C/min. Since the rate of temperature increase is greater for the highest concentration factor, the temperature difference between the two troughs changes from 11°C to 17°C on the same 24-minute period. In contrast to the case when the collector is open, the “smoothness” of both temperature curves here is due to the box being totally sealed (i.e. not affected by cooling fluctuations from wind gusts).

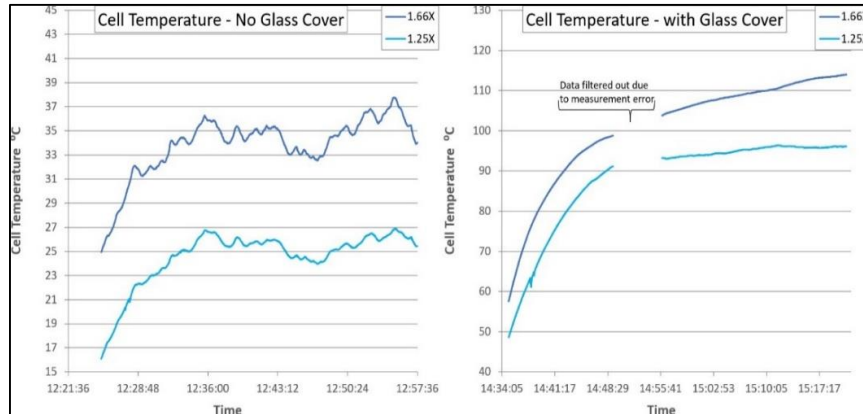


Fig. 13: Measurements of cell temperature over a period of 30-45 minutes with the collector at normal incidence. Left side: case (1). Right side: case (2).

4. Conclusions

At 60°, the 1.66X version shows an increment in YCE of around 29%, when compared with the 1.25X version. Simulations reveal the geometrical feasibility of the CPC design for its use on high-latitudes. Both versions present high electrical losses, as nearly half of the theoretically measured power is lost. Larger temperatures have been reached by the 1.66X version compared to the 1.25X, as expected. As the performance and lifetime of solar cells degrade with high operating temperatures, it is crucial to reduce the temperature in order to achieve and maintain collector's efficiency. Temperature curve trendline of the 1.66X version shows that this concentration can lead to operating temperatures higher than the 114°C obtained for the 1.66X version. IAMs suggest that the 24hc receiver of around 5-10% more susceptible to present reduced power as the incident angle changes from optimal. This difference might be attributed to the change in the cell layout between the two receivers. For instance, the half-cell string layout has double the amount of inter-cell gaps since it has double the cells. Using cut cells provides lower currents and reduces the resistance losses and prevent cells from overheating, thus it increases the efficiency from PV systems. Although this technique has been proved to be successful in previous works, both receivers tested, 12fc and 24hc, presented high resistance losses that account for nearly half the theoretical (rated) power to be lost as dissipated heat. This result is most likely caused by the hand soldering of busbars onto the cell and consequent microcracks. An answer to the unwanted heat generation and consequent efficiency reduction is the inclusion of appropriate ventilation designs to maximize passive cooling, which is in agreement with previous CFD simulations (Lança et al. 2018) showing a significant reduction of operating temperature in a CPC with added ventilation, even if only consisting in small side openings. Therefore, re-designing of the lateral gables and the inclusion of open sections will improve the thermal behaviour by increasing heat transfer with the outside environment. The final rate of temperature gain of around 0.4°C/min presented in Figure 14 strongly suggests that cell temperatures close to 150°C can be easily achievable for this concentrations, if exposed to higher irradiances, to extended periods of time and to higher ambient temperatures.

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6. References

- Almeco Group. Manufacturer of aluminum components and laminates. Retrieved February 3, 2019, from <https://almecogroup.com/en>.
- Arnaout, M., Salameh, W., Assi, A., 2016. Impact of Solar Radiation and Temperature levels on the variation of the series and Shunt Resistors in Photovoltaic Modules. *International Journal of Research in Engineering and Technology*, vol. 5, Issue 3, 295-301.
- Bader, R., Steinfeld, A., 2010. A Solar Trough Concentrator for Pill-Box Flux Distribution Over a CPV Panel. *Journal of Solar Energy Engineering*, 132(1), 14501–14504. Retrieved from <http://dx.doi.org/10.1115/1.4000597>
- Blanco, M. J., Amieva, J. M., Mancillas, A., 2005. The Tonatiuh Software Development Project: An open source approach to the simulation of solar concentrating systems. ASME 2005 International Mechanical Engineering Congress and Exposition, 157–164. American Society of Mechanical Engineers.
- Cabral, D., Gomes, J., Dostie-Guindon, P.-A., Karlsson, B., 2017. Ray Tracing Simulations of a Novel Low Concentrator PVT Solar Collector for Low Latitudes. *ISES Solar World Congress 2017*. <https://doi.org/10.18086/swc.2017.18.05>.
- CHT UK. Manufacturer of silicone products. Retrieved February 3, 2019, from <https://acc-silicones.com>.
- Daneshazarian, R., Cuce, E., Cuce, P. M., Sher, F., 2018. Concentrating photovoltaic thermal (CPVT) collectors and systems: Theory, performance assessment and applications. *Renewable and Sustainable Energy Reviews*, 81, 473–492. <https://doi.org/https://doi.org/10.1016/j.rser.2017.08.013>.
- Giovinazzo, C., Bonfiglio, L., Gomes, J., Karlsson, B., 2014. Ray Tracing Modelling of an Asymmetric Concentrating PVT. *EuroSun 2014*, (September), 16–19. Aix-les-bains, France.
- Hertel, J.D., Martinez-Moll, V., Pujol-Nadal, R., 2015. Estimation of the influence of different incidence angle modifier models on the biaxial factorization approach. *Energy Conversion and Management*, 106, 249-259.
- Kalogirou, S. A., 2014. *Solar Energy Engineering: Processes and Systems: Second Edition*. Elsevier Inc. <https://doi.org/10.1016/C2011-0-07038-2>.
- Kelly, N. A., Gibson, T. L., 2011. Increasing the solar photovoltaic energy capture on sunny and cloudy days. *Solar Energy*, 85(1), 111–125. <https://doi.org/https://doi.org/10.1016/j.solener.2010.10.015>.
- Lança, M., Gomes, J., Hayati, A., 2018. Numerical Simulation of the Thermal Performance of Four Prototypes of CPC Collectors That Use Bifacial PV Cells. *Proceedings of EuroSun 2018*, 1–12. <https://doi.org/10.18086/eurosun2018.02.25>.
- Mojiri, A., Taylor, R., Thomsen, E., Rosengarten, G., 2013. Spectral beam splitting for efficient conversion of solar energy—A review. *Renewable and Sustainable Energy Reviews*, 28, 654–663. <https://doi.org/https://doi.org/10.1016/j.rser.2013.08.026>.
- Nguyen, H., 2010. Minimizing Micro-cracks in Solar Cell Interconnection during Manual Soldering. Retrieved March 27, 2019, from *Renewable Energy World website* [Accessed: 27-Mar-2019]: <https://www.renewableenergyworld.com/articles/print/pvw/volume-2/issue-6/solar-energy/minimizing-micro-cracks-in-solar-cell-interconnection-during-manual-soldering.html>.
- Rolley, M. H., Sweet, T. K. N., Min, G., 2017. In-situ thermoelectric temperature monitoring and “Closed-loop integrated control” system for concentrator photovoltaic-thermoelectric hybrid receivers. *AIP Conference Proceedings*, 1881(1), 100001. <https://doi.org/10.1063/1.5001452>.
- Salloom, A.H., Abdulrazzaq, O.A., Ismail, B.H., 2018. Assessment of the Performance of Bifacial Solar Panels. *International Journal of Engineering and Technical Research*, vol. 8, Issue 7, 13-17.
- Sarbu, I., Sebarchievici, C., 2016. *Solar Heating and Cooling Systems: Fundamentals, Experiments and Applications*. Elsevier Inc.
- Stine, W. B., Geyer, M., 2001. *Power From The Sun*. [Online]. Available: <http://www.powerfromthesun.net/Book/chapter09/chapter09.html>. [Accessed: 04-Mar-2019].