

Article

Experimental Electrical Assessment Evaluation of a Vertical n-PERT Half-Size Bifacial Solar Cell String Receiver on a Parabolic Trough Solar Collector

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Abstract: A two-trough parabolic-shaped concentrating photovoltaic solar collector with a vertical half-size ‘phosphorus-passivated emitter rear totally diffused’ bifacial cell string receiver was designed and built for household applications, with the aim of smooth the electrical ‘duck curve’. The study consisted in testing the concentrating photovoltaic solar collector outdoors, under real weather conditions, for its daily electrical peak power and efficiency, as well as for its electrical transversal and longitudinal Incidence Angle Modifier direction. The outdoor testing measurements were conducted in a parabolic trough with low concentration coupled with a central vertical half-size ‘phosphorus-passivated emitter rear totally diffused’ bifacial cell string receiver. Furthermore, the electrical transversal Incidence Angle Modifier showed to be very delicate due to the position and outline of the receiver, which led to an electrical peak efficiency close to 10% at $\pm 25^\circ$ (i.e., for an electrical power output of around 49.3 W/m²). To validate the measured parameters, a ray-tracing software has been used, where the measured Incidence Angle Modifiers have a very good agreement with the simulated Incidence Angle Modifiers (e.g., deviation of <4%). Consequently, the concentrating solar collector met the objective of lowering the Photovoltaic cell stress and high radiation intensity, by shifting the electrical peak power at normal (e.g., at 0°) to higher incidence angles (e.g., $\pm 25^\circ$); this aids the electrical demand peak shaving, by having the highest electrical power production displaced from the highest intensity solar radiation during the day.

Keywords: concentrating photovoltaic solar collector; compound parabolic collector; half-size bifacial photovoltaic cells; phosphorus-passivated emitter rear totally diffused cells; collector testing



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1. Introduction

The most renowned and diverse source of renewable energy is indisputably the energy provided by the sun, solar energy, which can be divided into electrical and thermal energy. Photovoltaic (PV) technology (for electricity production) registered an exponential progress in the past 10 years with single-junction crystalline silicon (c-Si) solar cell technology that keeps demonstrating enhanced efficiencies as high as 27% [1], which is getting closer to 29% efficiency limit presented by Shockley-Queisser [2]. Therefore, several research projects are underway to further enhance the efficiency of different PV cell technologies, for instance, a four-terminal (4T) configuration could reach an efficiency of around 32.5% for a two-junction GaInP/Si cell [3] or an efficiency of 32.8% for a two-junction GaAs/Si cell, and 35.9% for a triple-junction GaInP/GaAs/Si cell [4]. A triple-junction GaInP/GaAs/Si cell with 33.3% efficiency has been reported [5], which is characterized by a two-terminal (2T) configuration. Additionally, a perovskite top cell with an interdigitated back-contact (IBC) silicon heterojunction (SHJ) bottom cell reached an efficiency potential of 27% [6].

The application of bifacial solar photovoltaics into a solar collector shows to be promising, as it has the potential to enhance the electricity production (on a square meter basis) of a standard PV panel by up to 30%. This is possible due to the back-side light absorption from either the albedo or reflector or a combination of both.

PERT is an acronym for passivated emitter rear totally diffused and is structured with a back surface being “totally diffused” with either boron (p-type) or phosphorus (n-type, typically used in PERT cells). This technology (PERT cell) takes full advantage of n-type Si wafers’ higher tolerance to metallic impurities, lower temperature coefficient and lower light-induced degradation than p-type Si wafers [7].

A transparent back-sheet is implemented to encapsulate PV panels and, therefore, to take advantage of the high-efficiency potential and low cost of the n-type monocrystalline bifacial solar cells, which makes them very attractive for investment [8]. Furthermore, when compared with a p-type solar cell, it has an enhanced I_{sc} , V_{oc} and filling factor (FF), which vary with solar irradiance and ambient air temperature.

Moreover, n-type silicon solar cells feature two key advantages (when related to the standard p-type boron-doped silicon bifacial cells). Firstly, they are not affected by light-induced degradation (LID) triggered by the presence of boron-oxygen imperfections in the wafers, where [9] showed that n-type PV modules have high resistance to potential-induced degradation. This phenomenon can lead to a decrease in the module’s electricity production by around 2–3% within the primary days of sunlight exposure. Secondly, the impurities found in silicon feedstocks are typically not found in n-type silicon wafers as this technology is less sensitive to impurities [10].

Typically, the reported efficiencies for n-type PV modules reach greater electrical efficiencies, up to 10%, than conventional PV modules composed of p-type monocrystalline bifacial solar cells. Moreover, n-type solar cells also show a higher electricity production at higher diffuse radiation levels, as it typically happens in cloudy day conditions [11]. Bifacial n-type silicon solar cell technology had an exponential growth regarding the bifacial ratio (which already reached >90%), which is the relative efficiency between the back and front sides of the solar cell [12]. Furthermore, a recent study showed that the bifacial power gain (when compared with standard PV modules) ranges between 13–35% and 40–70% under sunny and cloudy conditions, respectively [13,14]. Additionally, a single-axis tracker bifacial system can increase energy yield by 35% and reduce the levelized cost of energy by up to 16% when compared to standard PV systems [15].

From the bifacial module perspective, a share of sunlight illuminates the front side of the cells; meanwhile, the backside of the module collects sunlight that has been reflected from the ground surface [16] (Figure 1), or in modules with concentration the sunlight will be reflected from the reflective material.

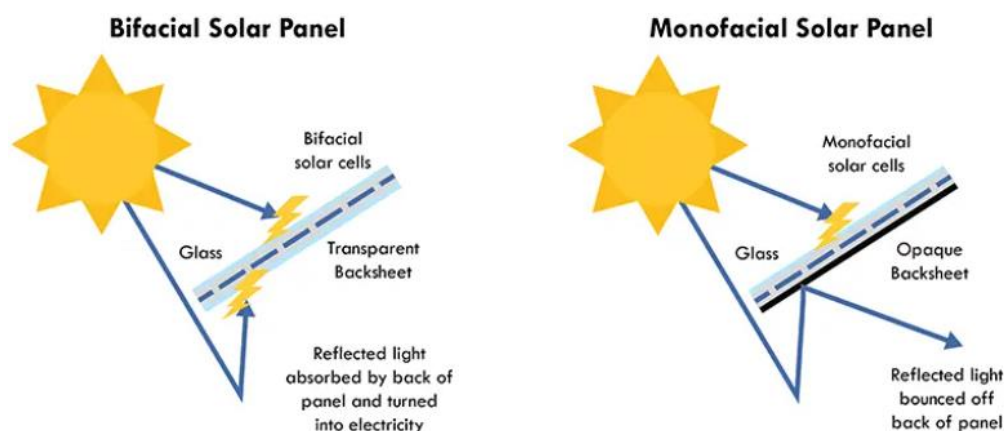


Figure 1. Schematic view of the reflection due to albedo in bifacial and monofacial PV panels (<https://couleenergy.net/bifacial-solar-panel-double-sided-solar-panels/>, accessed on 15 January 2023).

Bifacial PV modules can reach enhanced electricity production than a standard PV module; however, it is also extremely dependent on location, orientation, and placement conditions [17]. In 2020, the ENF Solar directory of solar companies listed around 184 producers of bifacial solar panels and according to the International Technology Roadmap for Photovoltaics, it will increase its share from 20% up to 70% of the overall PV market by 2030.

Conventionally bifacial PV modules tend to improve the electricity production due to the extra electricity produced from the light reflected or diffused to the rear side. Another approach is to mount these bifacial PV modules vertically, in which the electrical production peak profile in the morning and evening typically comprises a valley in between peaks, which matches the electricity load [18]. This improves the self-consumption of the electricity produced by the bifacial PV modules, which has been acknowledged as a crucial parameter for the economic feasibility of small-scale PV production when severe feed-in tariffs are not employed [19]. Furthermore, this also decreases voltage fluctuations [20] and the need for balancing the low voltage grid power [21], as a mismatch between PV production and the load is obtained.

Moreover, peak shaving involves proactively managing overall demand to smooth short-term peak demand, which smooths out peak loads and, therefore, reaches some benefits, such as:

- Commercial and industrial customer electricity bill reductions.
- During peak periods, utilities reduce the operational cost of generating power.
- Reduces the overall cost of demand charges.
- Sustainable operations.
- Eases the incorporation of Renewable Energy Systems into a more stable electrical grid.
- Lower reliance on carbon-based power sources and, therefore, reduce the carbon footprint.
- Flatter loads (e.g., reduced peaks) lead to deferred investment in infrastructures.

Typically, solar technologies (e.g., coupled with battery energy storage systems), demand response, energy storage system management, and restriction of PV generation are some of the most efficient ways to mitigate the commonly known ‘duck curve’, which presents the ‘*power production over the course of a day that shows the timing imbalance between peak demand and energy production*’ [22]. Furthermore, another way of lowering the peak demands is to mount bifacial PV modules as it will allow a higher output power during the peaks, and at the same time have fairly similar energy yields as a south-mounted PV modules [23].

Moreover, the average temperature of modules that have transparent back-sheets is $<3^{\circ}\text{C}$ than standard modules for the same environmental conditions [10,24], since the transparent back-sheet absorbs less infrared light which leads to lower module temperatures [25]. The temperature coefficient of modules with transparent back-sheet is $-0.22\%/^{\circ}\text{C}$ [26], while standard PV panels typically reach around $-0.35\%/^{\circ}\text{C}$ [27], which makes this technology (with transparent back-sheet) have more energy output than standard PV panels. On the other hand, an opaque back-sheet foil in monofacial module configurations avoids higher optical losses since it absorbs all radiation [11].

The efficiency of c-Si solar cells increments in the past decades and the exponential fall in manufacturing costs led to a higher interest by the markets and manufacturers in concentrating PV (CPV) technologies [28]. The most common strategy to enhance the PV panel efficiency is by texturizing the surface of a solar cell to increase the absorption of light, which can even be further improved by adding reflectors/mirrors to the PV panels, which also reduces the overall cost of PV modules [29]. Using a solar concentrator coupled with PV cells (CPV) for electrical power generation is an effective approach to increase the output power and reduce the investment cost, as the number of solar cells will be reduced [30]. Mono-crystalline silicon solar cells are the most common solar technology used for electrical power generation [31] and are commonly used in solar systems [32,33].

These systems are differentiated according to the concentration ratio and more than 90% of the CPV capacity publicly documented comprises mostly high-concentration PV (HCPV) with two-axis tracking systems [34]. The concentration of sunlight by a factor of 300–1000 in a small cell area supports the need to implement highly efficient but comparatively more expensive multi-junction solar cells. On the other hand, high-concentration solar systems produce non-uniformity patterns on the solar cells (i.e., lower open-circuit voltage V_{oc} vs. uniform illumination), which leads to low photoelectric efficiencies (i.e., increased effective series resistance) [35,36]. Thus, a solar concentrator with higher light uniformity would improve the overall efficiency of CPV systems [37–39]. Concentrating photovoltaic systems (vs conventional c-Si solar cells) have higher incident illumination intensities due to the enhanced solar radiation provided by the reflective materials and thus a non-uniform illumination distribution [36]. On the other hand, low-concentration photovoltaic systems (LCPV) are typically built with concentration ratios below 100 suns and primarily use mono c-Si solar cells and single-axis tracking but can be also attached to a dual-axis tracking system [2]. These systems (LCPV) can also have very low concentration factors from 2–10 suns [40], which are very appropriate for building integration [16] since their lightweight and larger acceptance angles θ_c are of most interest for this kind of application [39].

Furthermore, by adding a simple booster reflector (typically parabolic troughs or dish concentrators, [41]) the solar electric output can increase by over 30% more than conventional PV systems [42]. In addition, [43] showed that the coupling of LCPV with bifacial PV cells can enhance electrical production by >1.5x in comparison with standard stationary PV panels.

Literature shows that the electrical performance of CPV technologies is directly dependent on the amount of direct and/or diffuse radiation. This is of most importance in locations with high cloudiness intensity, where the available direct and diffused radiation can vary substantially throughout one day [44].

Consequently, the low-concentration CPV solar collector presented in this paper aims at lowering the PV cell stress and high radiation intensity, by shifting the electrical peak power to higher incidence angles, which addresses one of the most critical problems PV cells encounter (e.g., PV cell stress and degradation) when placed under real sunny conditions.

Moreover, at medium-high latitudes, the tilt of any solar collector for a standard household requires a high tilt angle, due to the asymmetry of the solar radiation profile. PV modules are often used as a primary source of power for a heat pump of any storage that requires electricity at higher latitudes, which leads to the installation being optimized for the winter months, where the sun altitude is fairly lower. Typically, it is required that new foundations/structures are built to fulfil this requirement for high electrical efficiency, which sports higher costs, and without any viable subsidies, the installations are not carried out.

Therefore, the CPV presented in this manuscript is intended to be a suitable solution for medium-high latitude installations as it defocuses the high-intensity radiations at normal incidence to lower intensity radiations at lower incidence angles and, at the same time increases the required electrical efficiency without the need for any extra costs on foundations/structures to tilt the collector. At medium-high latitudes, the low sun height presents several constraints for high electrical production, as the angle of incidence is not optimal, especially during winter, therefore this CPV layout overcomes, partially, some of the limitations for lower sun altitudes.

No solid literature is available on CPV for low concentrations (e.g., for household applications); therefore, by addressing this issue, the lifespan of PV cells can be enhanced and provide a better insight into smaller energy communities. Several studies on high concentration ratios for CSP are available [45–50] but do not fit the aim of this manuscript, which is to address the previously mentioned issues while providing reasonable efficiency for households.

The high energy demand consumption of indoor temperature control devices urges the decision makers to invest and use renewable energy technologies for these applications to decrease the use of high non-renewable energy resources and mitigate severe weather patterns. Solar collectors, which are competitive and are already an established technology, lack implementation directives and strong subsidies. Due to their potential for low cost and wide penetration for local energy production, CPV solar collectors are a solar technology that can alleviate severe weather events as a primary source for minimum energy consumption from different indoor control applications. At typical locations where severe weather events are often, especially in the winter time.

Additionally, this manuscript presents the potential of CPV solar collectors as a good solution for competing with bifacial PV modules, as it is not influenced by the shading effect from other CPV rows. This way the CPV allows the installation of more CPV solar collectors, with minimal distance between rows, which will optimize the installation area and at the same time lower the requirement of longer cabling, thus lowering the overall cost of the solar collectors' installation. The presented CPV solar collector can also be a good solution for BIPV solar installations due to its small dimensions (e.g., thickness).

Therefore, to reach the aim of this manuscript, several sets of electrical experimental tests are presented, such as Incidence Angle Modifier (for both transversal and longitudinal directions) charts, daily performance diagrams, as well as electrical efficiency measurement diagrams. The described testing performed in this manuscript aims at providing a complete report for the implementation of these devices, based on high electrical production with the potential of lower costs, in medium-high latitudes, which lacks high electrical performance during the winter periods.

Moreover, and for a better-read flow, the presented study has been divided into four main sections such as Section 1. Introduction; Section 2. Experimental test method description; Section 3. Results and Section 4. Conclusions.

2. Experimental Test Method Description

2.1. Low Concentration Photovoltaic Solar Collector Description

The study assessment made on the CPV solar collector presented in this article started with the construction and placement in the solar laboratory at the University of Gävle and was tested during the summer months of 2019.

The vertical glass receiver is composed of 24 half-size n-PERT bifacial cells, which were hand-soldered and connected in series. Moreover, the receiver is located on the bottom center of the parabolic trough, which has a total aperture of 323 mm and a reflector height of 133 mm (Figure 2).

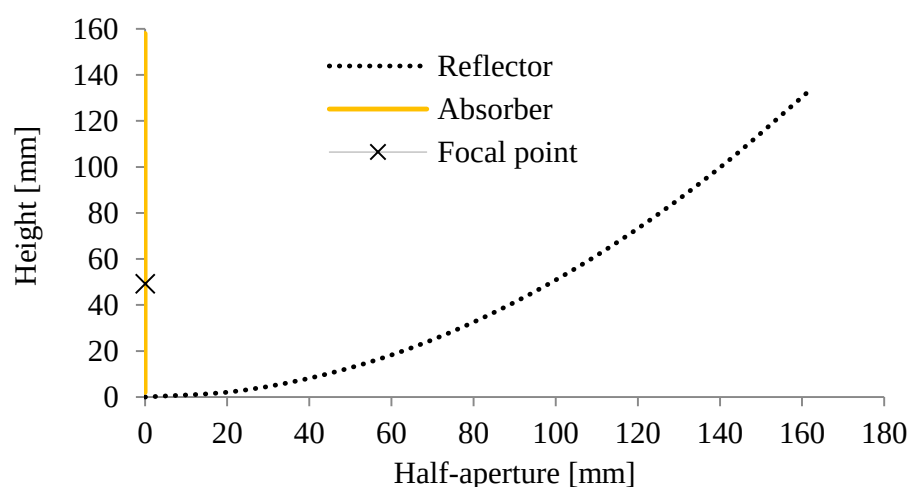


Figure 2. Cross-section view of the parabolic trough solar collector with vertical n-PERT bifacial cell string.

The aim behind the receiver being higher than the reflector is to increase (in the transversal direction) the amount of direct radiation received and, therefore, not heat the bifacial cells excessively. The design concept seats in a collector box with a height of 175 mm and a length of 2440 mm. Moreover, a reflector material with a spectral reflectivity (in the visible range) of $\rho = 92\%$ has been provided by Almeco (model Vega 295SP) [51].

The vertical bifacial glass receiver is composed of 24 half-size n-PERT bifacial solar cells connected in series (encapsulated in a silicone gel Elastosil Solar 2205 (Wacker), characterized by a thermal conductivity of 0.2 W/m.K and a light transmittance of 97%). The mechanical support is given by a low iron solar glass sheet with an outer width of 158 mm and a length of 2000 mm. The encapsulation of the cells leads to a total receiver thickness of 7 mm (4 mm for the low iron solar glass sheet; 3 mm for the silicone gel and PV cells).

The selected bifacial solar cells presented in this electrical performance assessment are phosphorus-doped n-type wafers with a thickness of around $200 \pm 30 \mu\text{m}$ as a substrate with an electrical efficiency of 19.6%. The front side (positive electrode) has an alkaline texturized surface, a Blue SiN x ARC coating and 3 busbars. The back/rear side (negative electrode) has a Blue SiN x ARC coating and 3 busbars. The electrical characteristics of the tested bifacial PV cell are presented in the following Table 1.

Table 1. Summary of the main parameters for the geometry design concept.

Efficiency [%]	P_{mpp} [W]	V_{vpp} [V]	I_{vpp} [A]	V_{oc} [V]	I_{sc} [A]	Dimensions [mm]
19.6	2.4	0.53	4.4	0.63	4.7	78×156

Furthermore, this PV technology has a lower temperature coefficient than p-type modules, leading to an enhanced electrical production on sunny (warm) days (vs standard PV modules). Moreover, the n-PERT bifacial cells have been cut in half ($78 \times 156 \text{ mm}$) since this method (of cutting PV cells in half) has garnered significant research attention from the PV manufacturers due to enhancing the electrical power output. Haedrich et al. [11] reported that halved c-Si solar cells can reduce efficiently cell-to-module (CTM) losses by lowering the series resistance loss. Furthermore, Xi et al. [25] showed that laser-cutting PV solar cells, is the major source of losses on n-PERT bifacial cells, but on the other hand, n-PERT bifacial cells can maintain high efficiency and excellent reliability (under optimal cutting conditions). Additionally, by having half-size PV cells, the theoretical maximum power point P_{mpp} and the short-circuit current I_{sc} are cut to half of an equivalent full-size PV solar cell, whereas the open-circuit voltage V_{oc} should be equal to a full-size PV cell. Furthermore, for different albedo conditions, the electrical power and, therefore, the efficiency of each n-PERT bifacial cell will be different and, therefore, presented in Table 2.

Table 2. Summary of a full-size n-PERT bifacial cell for different albedo conditions (data presented in the manufacturers' datasheet).

Efficiency Class	Front Side	Back Side–Albedo		
	-	10%	20%	30%
Efficiency [%]	19.6	21.5	23.2	25.1
P_{mpp} [W]	2.4	2.6	2.8	3

Additionally, the main parameters of the low iron solar glass for both the collector cover and receiver structure are presented in the following Table 3.

Table 3. Low iron solar glass for both collector cover and receiver structure parameters.

Emissivity [%]	Thickness [mm]	Thermal Conductivity [W/m.K]	Transmittance ¹ [%]
83.7	4	1	91 [+/-2.5]

¹ Reference to ISO 9050.

2.1.1. Electrical Performance Characterization

The electrical performance characterization of a concentrating PV solar collector typically takes into account the instantaneous performance ratio (PR_{IAM}) due to incidence angle losses [23], which is given by Equation (1).

$$PR_{IAM} = 1 - b_0 \left(\frac{1}{\cos \theta} - 1 \right) \quad (1)$$

where b_0 stands for the constant for the incident angle modifier. Additionally, the influence of the temperature dependence on the electrical efficiency PR_T , is also accountable and expressed as Equation (2) [52].

$$PR_T = 1 - \beta \cdot (T_{cell,PV} - T_a) \quad (2)$$

where the temperature coefficient of the electrical power is given by β , whereas the PV cell mean temperature is presented by $T_{cell,PV}$ [53]. For low-concentration factors, the low irradiance behaviour PR_G parameter [54] is typically ignored. Therefore, the instantaneous electrical power P_{el} , which comprises PR_{IAM} , PR_T , and $\eta_{el,STC}$, can be expressed as follow (Equation (3)).

$$P_{el} = \eta_{el,STC} \cdot PR_{IAM} \cdot PR_T \cdot G \quad (3)$$

2.1.2. Ray-Tracing Software

The National Renewable Energies Center (CENER) developed Tonatiuh (<https://tonatiuh.software.informer.com/>, accessed on 5 January 2023), which is an open-source ray tracing software that assesses the optical solar collector simulation constraints while designing complex Concentrated Solar Power (CSP) systems. Tonatiuh has been developed on a C++ programming language, which is based on a Monte Carlo Ray-Tracing Method (MCRM).

Blanco et al. [55] experimentally validated Tonatiuh's Graphics User Interface with real experimental data obtained from different CSP projects. The software allows the simulation of complex concentrating systems using several sets of materials, a built-in tool for calculating flux distributions and the capability to import CAD files to optimize the light ray's path.

While setting the concentrating system model, it is required that several nodes and sub-nodes, that are structured in a tree setup, must be described (i.e., properties applied to a specific node also apply to all the sub-nodes). The software offers a wide range of shapes and material nodes to define the surfaces of the concentrating system.

Moreover, after setting up the solar system in the software, it is required that the user defines the Sun (i.e., light source) by position, azimuth and elevation angles, and a Pillbox sun shape.

The sun, which is considered as the software light source, generates a specific number of light rays, which are set by the user, and instantaneously calculates the ray intersection/path (i.e., sunlight rays are launched and traced) with the concentrating system surface. The intersection of the light rays with the concentrating solar system is calculated from the initial point at the source node. Additionally, the intersection between a ray and a node bounding box is verified by a sub-node [56].

To assess the required IAM profiles, it is necessary to use a built-in extension from Tonatiuh, where the sun position is changing (e.g., from 0° to 180°) in one direction while the other is constant (e.g., at 90° , perpendicular to the CPV collector plane). Whenever this process is done, the direction that was previously fixed is now subjected to changes, while the other remains constant. The number of launched rays was set to 10^7 rays for higher precision.

The optical analysis used to assess the Incidence Angle Modifiers profile has been based on the main principles of radiation transmission through glazing (Duffie and Beckman, 2013) [42], which assesses the unpolarized radiation reflectance and transmittance.

The software is not able to study the influence of a bifacial PV cell neither evaluate the possible transparency between PV cells; therefore, two single-sided PV solar cells have been used to get a good comparison and provide the main advantages of this technology.

The extracted data from the Tonatiuh software is then processed in a MATLAB script [54], which has an electrical performance model (described in Section 2.1.1), to evaluate the electrical transversal and longitudinal IAM.

2.2. Testing Equipment Description

The setup, through an I-V tracer, can measure electrical peak power, voltage and current (P_{mpp} , V_{mpp} and I_{mpp} , respectively), short-circuit current I_{sc} , open-circuit voltage V_{oc} and solar radiation G (both global and diffuse). The CPV collector has been placed at the outdoor testing facility at the University of Gävle, in Gävle, mid-Sweden. Moreover, depending on the type of testing performed, the collector has been mounted with a variable south-oriented collector tilt angle (β).

Furthermore, a KippZonen CMP6 and CMP3 pyranometer were placed in the same plane as the solar collector to measure both solar global and diffuse radiation, respectively. Additionally, all measurement equipment has been connected to a Campbell Scientific CR1000 datalogger to record and monitor the data. The following Table 4 presents the accuracy of each measurement device.

Table 4. Electrical measurement equipment and respective accuracy deviation, for a 30 s time-step.

Measurement Equipment	Data	Deviation
Pyranometer CMP3 [W/m^2]	Up to 2000	$\pm 1.5\%$
Pyranometer CMP6 [W/m^2]	Up to 2000	$\pm 1\%$
I-V Tracer [V] [I]	-	0.1%

2.3. Outdoor Testing Method

2.3.1. Daily Electrical Performance

The electrical daily performance and electrical efficiency per gross area assessments were developed by placing the CPV system in an east-west orientation, for a specific tilt throughout the testing days (at the coordinates: 60.67° N, 17.14° E). The outdoor testing methods followed the methodology applied by [57].

2.3.2. Electrical Incidence Angle Modifier Testing Method

The effective south projection angle θ_{NS} (shown in Figure 3), sets the optimum tilt angle for a solar collector surface facing south in the northern hemisphere and it has been used in this study to get the optimum collector tilt angle for the given days.

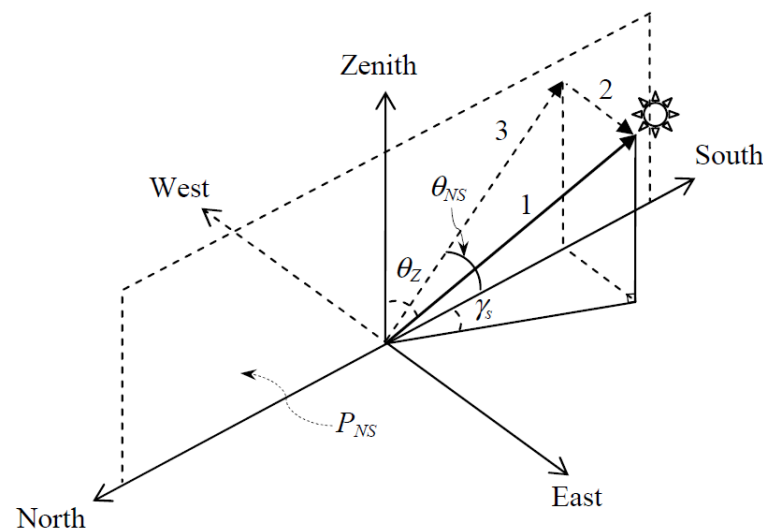


Figure 3. Vector 1 (solar position) has been split into vector 2 (east-west direction) and vector 3 (north-south vertical P_{NS} plane). Where γ_s the solar azimuth angle and θ_z is the solar zenith angle [58].

Typically, the south projection angle is constant during the entire day at the equinoxes, which means that the sun will move in an east-west plane that is normal to the glass cover (for a tilted angle equivalent to the latitude angle). Furthermore, the testing procedure to acquire the electrical Incidence Angle Modifier (IAM), consisted of placing the collector at the same tilt as $90-\theta_{NS}$ given for the 28th of July, between 11 am and 2 pm (Figure 4), which gives a collector tilt of around 42° .

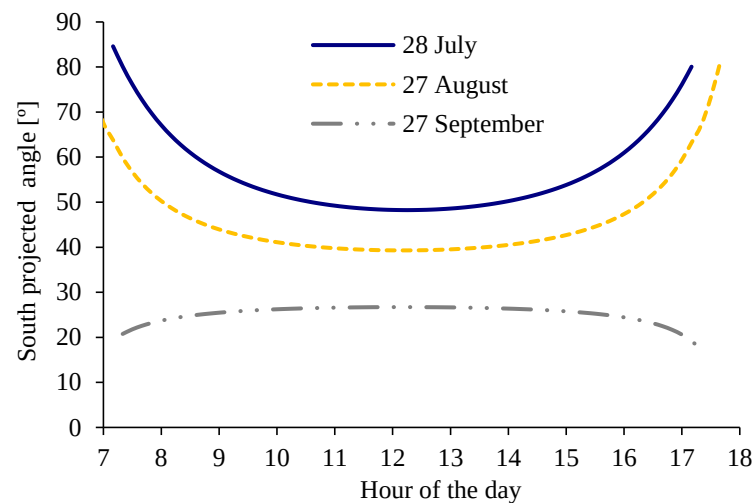


Figure 4. South projected angle θ_{NS} for 3 different days in July, August, and September for Gävle (Sweden).

For measurements of the longitudinal electrical IAM, the collector has been placed as presented in Figure 5 during the equinox. This way, no correction factors are needed, as the transversal incidence angle θ_T is negligible. Figure 4 presents the solar collector test stand for the electrical IAM (longitudinal direction, east-west solar collector placement) measurements, with the respective pyranometers that measure both global and diffuse radiation and were placed in the same plane as the solar collector.

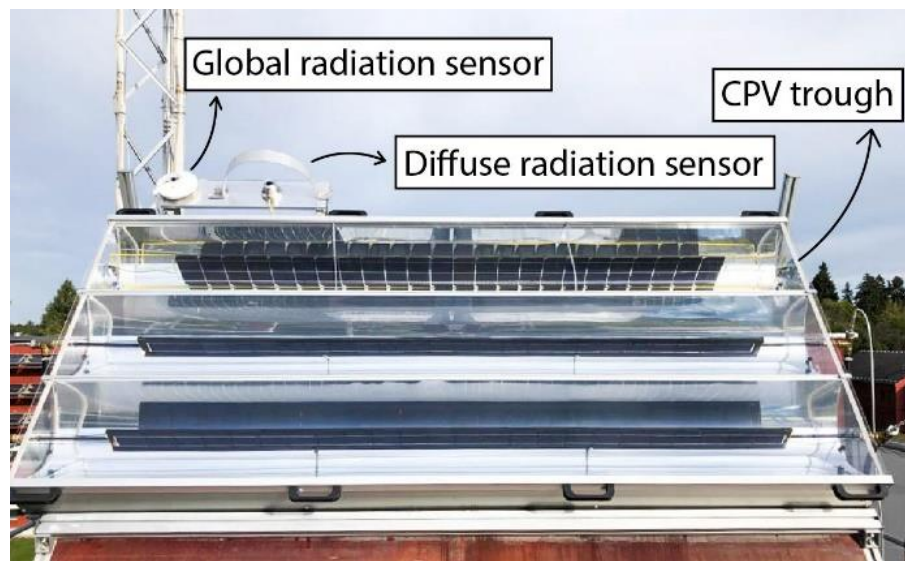


Figure 5. Solar collector test stands for the electrical IAM (longitudinal direction) measurements.

For the transversal electrical IAM measurements, the collector has been rotated 90° and placed in a north-south position as can be seen in Figure 6. Figure 6 presents the solar collector test stand for the electrical IAM (longitudinal direction, north-south solar collector placement) measurements, with the respective pyranometers that measure both global and diffuse radiation and were placed in the same plane as the solar collector.

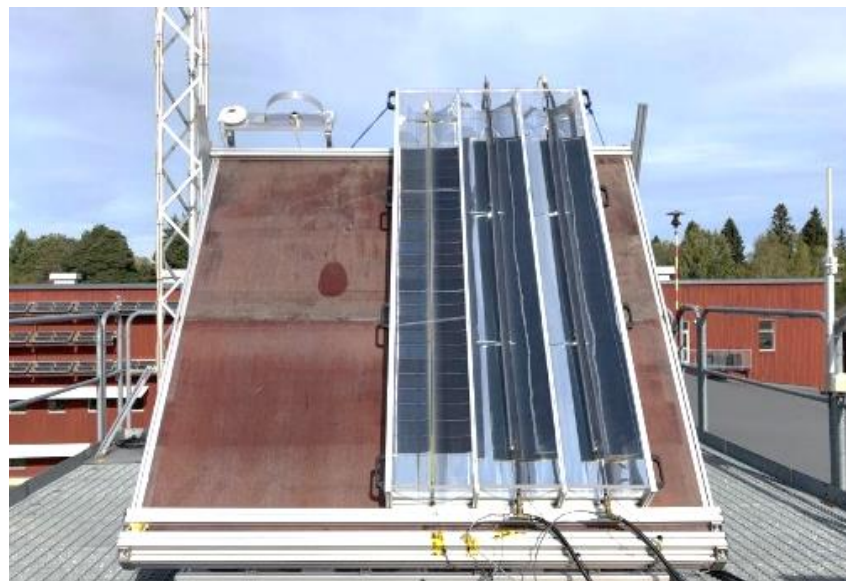


Figure 6. Solar collector test stands for the electrical IAM (transversal direction) measurements.

Additionally, the CPV solar collector was tested (in a north-south position as seen in Figure 5), for two days during summer, for a daily electrical peak power diagram to access and validate the transversal electrical IAM described previously. The relation between both transversal and longitudinal incidence angles, θ_T and θ_L , with the solar collector normal are presented in the following Figure 7.

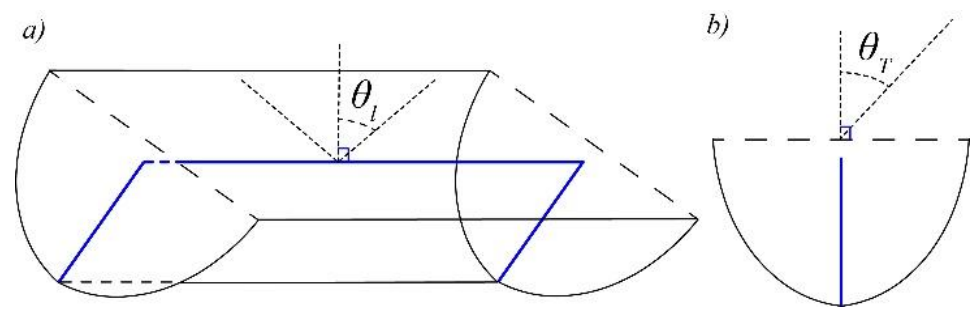


Figure 7. (a) Longitudinal incidence angle concerning the solar collector normal; (b) Transversal incidence angle concerning the solar collector normal.

3. Results and Discussions

A detailed comparative analysis of the electrical IAM for both transversal and longitudinal directions, as well as the electrical daily power and efficiency diagrams, are presented in the following section.

The overall goal of this study is to assess the performance behaviour of half-size n-PERT bifacial cells coupled with a parabolic reflector, through daily electrical measurements, as well as by assessing the electrical Incidence Angle Modifier, both in the transversal and longitudinal direction. The solar collector components were designed to smooth the 'duck curve' of the electrical grid power production. The CPV trough is located above two LCPVT troughs which makes the hot air travel upwards, enhancing this way the temperature of the CPV trough and lowering the electrical power.

Two days, in July and August, have been selected for the daily performance assessment of the LCPV solar collector for variable collector tilt angles.

3.1. Outdoor Electrical Measurements

The electrical efficiency profile data reveals the high sensitivity of the reflector geometry design concept coupled with bifacial cells, as it is more efficient when the collector is not placed at normal incidence with the sun rays (introduced in Section 3.3).

Moreover, the collector tilt angle does not necessarily optimize the collection of the incoming sun rays; therefore, it is necessary to adapt the collector tilt angle to achieve higher efficiencies, which is analyzed in the upcoming sections. For this reason, it was expected that for lower collector tilt angles the electrical efficiency would drop significantly.

Additionally, and for a clear sky day on the 28th of July, the collected electrical peak power data for the interval between 7:40 a.m. and 3:57 p.m. has been selected (i.e., steady projected solar altitude), for a collector tilt angle of 42° . As the PV cell temperature influences the electrical power output, it is important to follow and understand the electrical profile parameters concerning the instantaneous electrical power production (retrieved every 10 min), which is shown in the following Figure 8.

The electrical peak power profile presented in Figure 8 is in line with the predicted electrical efficiency profile shape since the solar radiation intensity is lower in the mornings/afternoon and higher at midday, thus a lower output in the morning/afternoon and a higher electrical output during midday if the correct collector tilt is applied. From the electrical peak power profile, it is possible to realize that the collector and the pyranometer have a minor misalignment since the electrical peak power is not located at around 12:23 pm (as in Figure 8) but at 12:10 pm (angle of incidence of 0°), corresponding to a deviation of around 3° towards the east, as one hour typically compresses 15° . Nevertheless, the electrical profile follows the solar radiation profile with electrical peak power at normal incidence of around 25 W/m^2 at 25°C of ambient air.

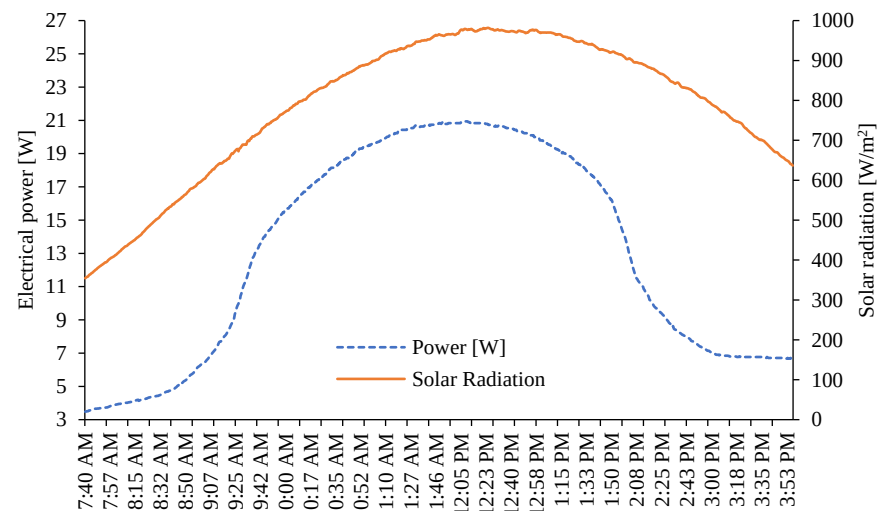


Figure 8. Measured electrical power (in Watts, left Y-axis) and solar radiation (in W/m^2 , right Y-axis) registered for a clear sky day on the 28th of July, south-oriented (for an east-west collector placement).

3.2. Electrical Outdoor Measurements

Daily Electrical Power Diagram

The following sub-section aims to study the daily electrical performance of the solar collector prototype for a collector tilt angle of 42° , while the theoretical tilt angle (for overall maximum performance) for 27th of August is around 51° (from Figure 4: θ_{NS} is around 39° ; therefore, we have $90 - \theta_{NS}$, which will lead to 51°), which is 11° off the selected collector tilt angle. Moreover, Figure 9 presents the daily electrical power per gross area (time-steps retrieved every 10 min).

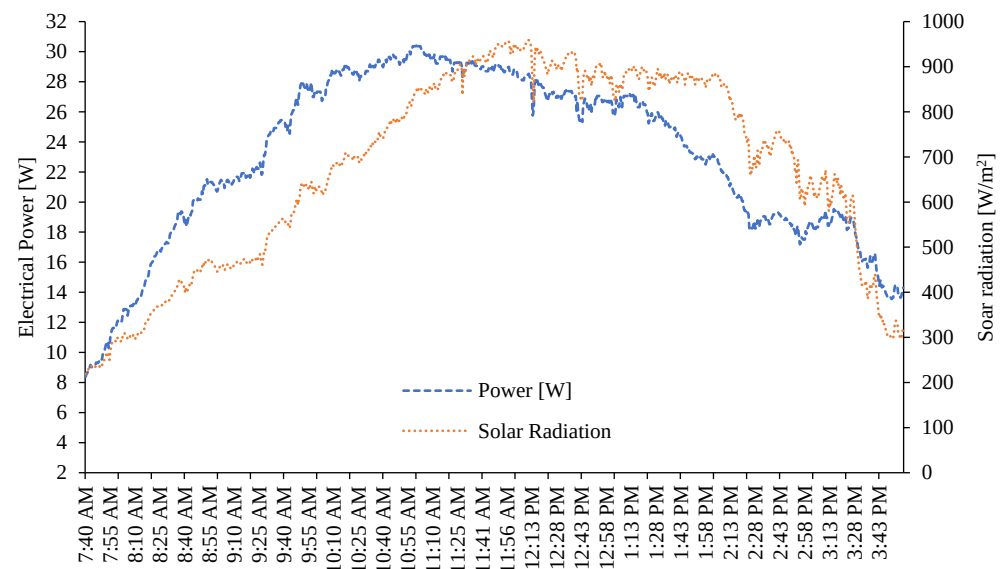


Figure 9. Electrical power (in Watts, left Y-axis) and solar radiation (in W/m^2 , right Y-axis) registered for a clear sky day on the 27th of August, south-oriented (for an east-west collector placement).

To achieve the highest electrical power output, it is imperative to adjust accordingly the collector tilt angle for the testing period. For this specific case, the solar collector plane tilt angle should have been around 51° if electrical peak power assessment (at normal incidence) was the study objective. However, this assessment aimed to assess the influence of the solar collector tilt angle on the electrical peak power output. Figure 9 shows the daily electrical peak power registered (for a time-step retrieved every 10 min) on the 27th of August.

The deviation of the collector tilt angle (42°) and the theoretical tilt angle (51°) leads to a mismatch between the electrical peak power and the solar radiation peak. This phenomenon is very clear in Section 3.3, as at normal incidence the collector is not as efficient as at incidence angles of around $\pm 25^\circ$. This way, the electrical profile follows the solar radiation profile (with some misalignment) and has an electrical peak power of around 30.4 W/m^2 at 22°C of ambient air.

Regarding electrical efficiency, two peaks have been registered at 9 am and 3:55 pm of around 4% per gross area. On the other hand, at midday, electrical efficiency reaches its lowest value (of around 2%) for the given day. Figure 8 shows that the bifacial n-PERT PV cells at normal incidence are not able to carry all the current in their ‘fingers’, which leads to higher outputs whenever the incidence angles are higher than 0° . Moreover, it is important to state that the PV cell string was hand-soldered, which leads to lower performance and, therefore, lower overall peak electrical efficiencies. Depending on the technology, the power drop can reach up to 9%.

3.3. Electrical Incidence Angle Modifier Measurements

In this section, the longitudinal and transversal electrical IAM has been addressed, following the testing method previously defined in sub-Section 2.3.2. As previously described, the electrical IAM has been attained by combining different parameters, such as the angle of incidence, global irradiation (W/m^2 , accounting for a mean value of $10\%_{\text{rel}}$ for diffuse radiation) and electrical power (W/m^2). Furthermore, the following Figure 10 shows the normalized outdoor testing diagram for the longitudinal IAM, as well as the simulated electrical IAM.

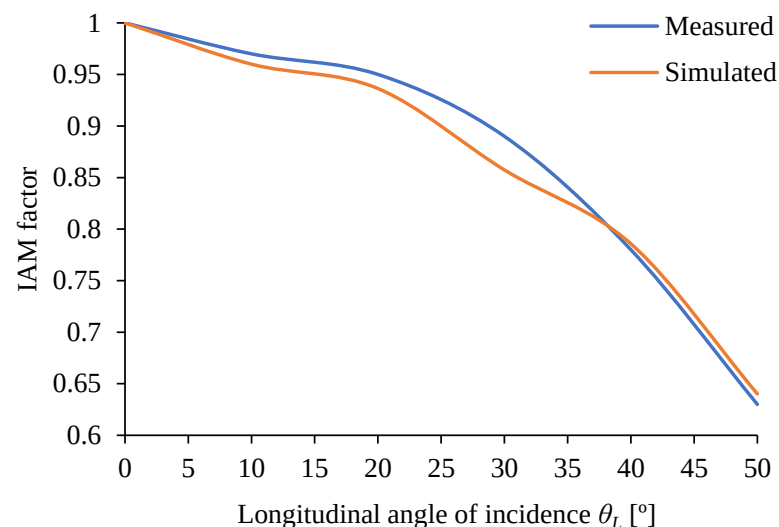


Figure 10. Normalized experimental and simulated electrical IAM for longitudinal direction.

Where the IAM factor corresponds to the decrease in the actual irradiance reaching the PV cells’ surface, with respect to irradiance under normal incidence (IAM factor of 1), due to reflections increasing with the incidence angle (e.g., where 0° corresponds to the irradiance under normal incidence). The normalized experimental electrical IAM (longitudinal direction) profile follows the expectation since the higher value lies at normal incidence with a constant decrease until incidence angles of around 50° . Moreover, there is an almost perfect fit between both measured and simulated, as the bifaciality does not affect the IAM (longitudinal direction).

Furthermore, Figure 11 shows the normalized transversal outdoor testing IAM diagram, where the highest electrical efficiency is obtained at $\pm 25^\circ$ and the lowest at normal incidence, for the measured IAM, whereas the simulated IAM (which comprises two single-sided PV cells, due to software restrains) has its peak at normal incidence.

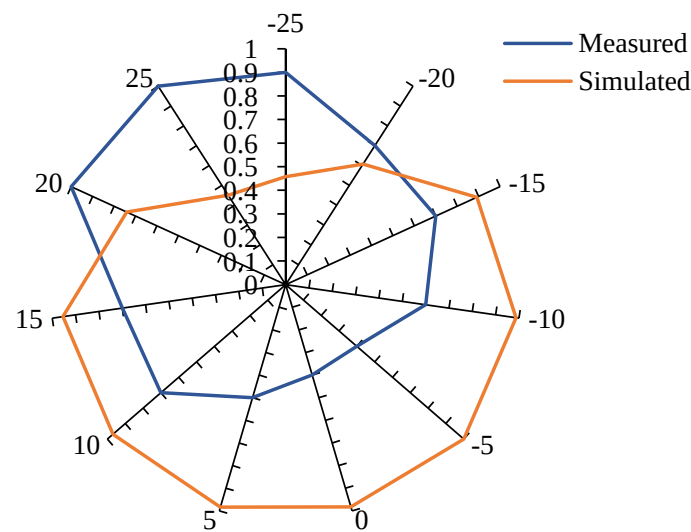


Figure 11. Normalized experimental and simulated electrical IAM for transversal direction.

From Figure 11 it is possible to visualize to which side the back side of the n-PERT bifacial cell was oriented since the bifacial ratio of the tested PV cells is around 90%, which is given at -25° of incidence.

On the other hand, the simulated transversal IAM profile shows that 2 single-sided PV solar cells do not manage to shift the high intensity at normal incidence (i.e., 0°). The losses in the transversal IAM profile due to the bifaciality are comprised between 0° and 20° . Nevertheless, this loss is then compensated by the wide range of electricity production at times of the day (i.e., morning and afternoon) when the demand is higher. This way, it is clear, that the bifacial PV cells are a suitable solution for grid flexibility, as it manages to have their peak power at times of the day when the demand is higher, which allows the ‘duck curve’ to flat out, which is of the highest importance from the grid perspective.

The importance to present the measured (bifacial PV cells) and simulated (two single-sided PV cells) is that by changing the PV cell technology it is possible to still have high performance and less PV cell degradation, and at the same time be able to cope with the flexibility required by the grid.

3.3.1. IV Curve Measurement (Transversal Direction)

The I_{sc} , V_{oc} , P_{max} , FF , V_{mpp} and I_{mpp} can be retrieved by following the IAM testing procedure. Characteristically, the electrical efficiency decreases with the increment of the incident angles, in which, up to the theoretical acceptance angle of $\pm 25^\circ$, the measured optical efficiencies have a slow decrease in relation to the theoretical optical efficiency pattern.

For incident angles higher than the theoretical acceptance angle the difference increases due to reflector imperfections (i.e., manufacturing problems and material scattering) and, therefore, imprecise reflections. Furthermore, for different incidence angles the focal line shifts transversely along the PVT receiver, hence the series resistance will vary as the edge busbar tend to carry most of the generated electric current.

On the other hand, the CPV solar collector presented in this manuscript tends to contradict the stated previously, where the highest peak is given at the acceptance half-angle of the CPV solar collector of $\pm 25^\circ$. Therefore, IV curves, that support the IAM measurements in the transversal direction are presented below in the following Figures 12–14 and Table 5.

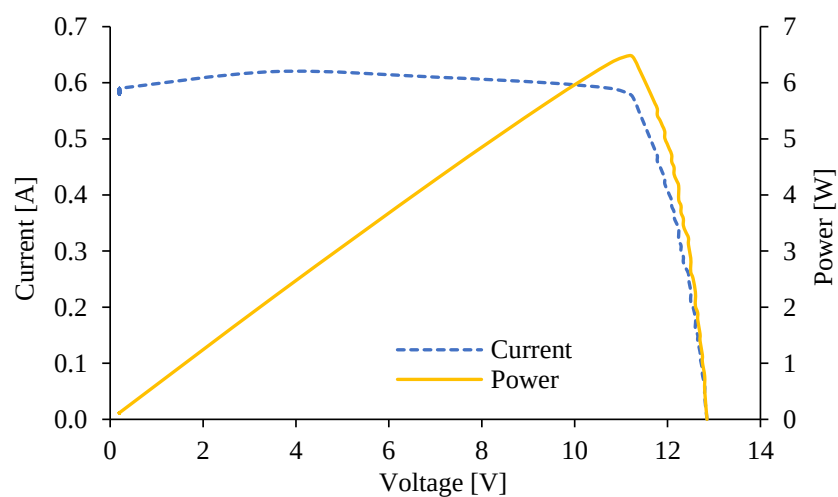


Figure 12. IV curve at normal incidence.

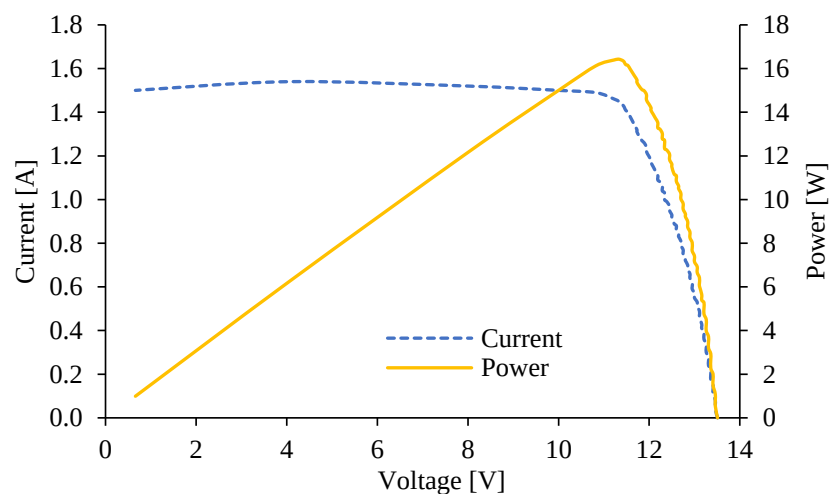


Figure 13. IV curve at 15°, transversal direction.

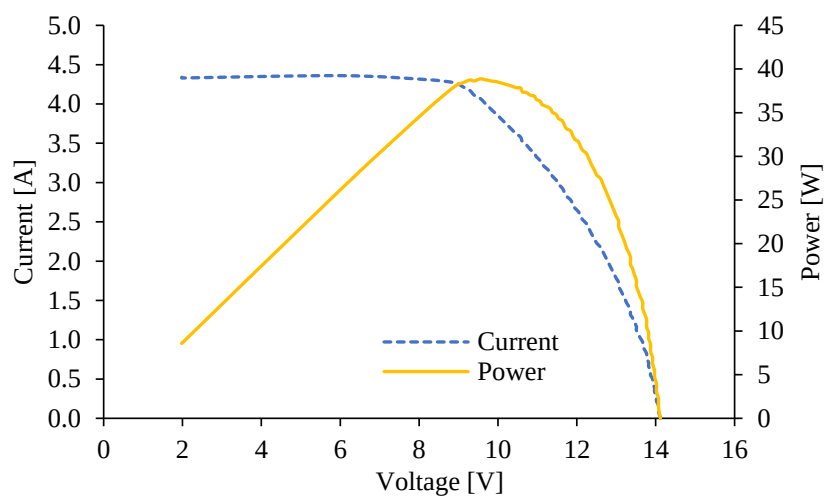


Figure 14. IV curve at 25°, transversal direction.

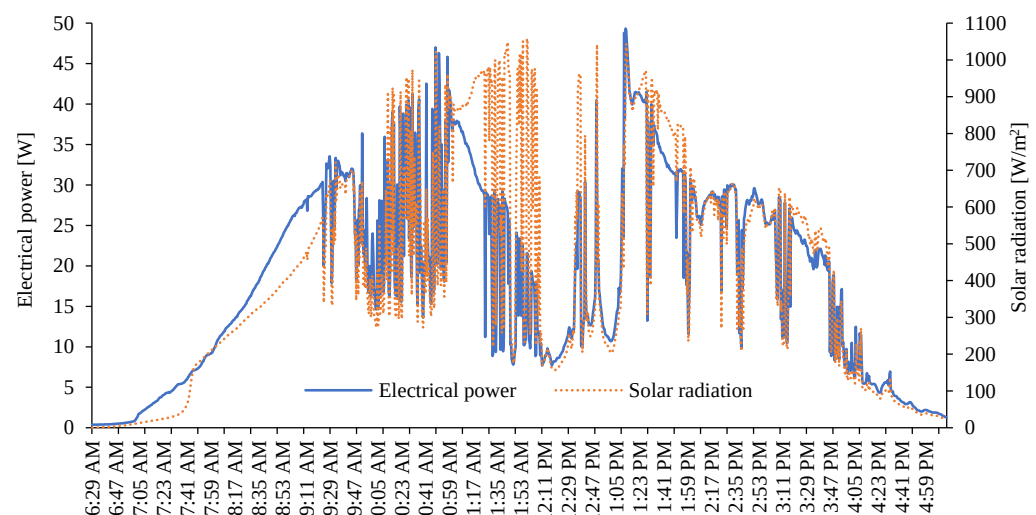
Table 5. Electrical parameters at normal incidence, 15° and 25°.

Parameters	0°	15°	25°
V_{oc} [V]	0.6	1.5	4.4
I_{sc} [A]	13	14	14
P_{max} [W]	7	16	39
V_{mpp} [V]	0.6	1.5	4
I_{mpp} [A]	11	11	10
FF [%]	81	79	63

From Figures 11–13 it can be observed that the CPV has the ability to shift the power intensity towards a higher incidence angle which matches the high peak grid demands.

3.3.2. IAM Validation Pattern

Furthermore, to validate the transversal electrical IAM presented in Figure 10, the collector has been placed as shown in Figure 6 and the measurements were recorded on the 27th of September (where the projected solar altitude is fairly a straight line, as can be seen in Figure 4), which makes this assessment very well suited for validation of Figure 10. The transversal electrical peak power for the 27th of September is given by the following Figure 15.

**Figure 15.** Transversal electrical power (left Y-axis) and solar radiation (right Y-axis) profiles (both in W/m^2), on the 27th of September.

The electrical peak power obtained for the 27th of September (Figure 15) is twice as high as the days presented in Section 3.2, with a maximum value of 49.3 W (which represents $78 W/m^2$). This shows that this specific geometry coupled with a vertical bifacial receiver is very sensitive not only due to the tilt angle but also due to the position (north-south or east-west placement in the test stand). Furthermore, the results presented in Figure 13 influence the longitudinal incidence angle θ_L since the collector had a collector tilt of 51° instead of the optimum theoretical solar collector tilt angle of 61° for Gävle (at equinox).

For a better understanding, the expected electrical power profile has been drawn, which considers the highest point of the measured instantaneous electrical peak power during the 27th of September. This profile has been drawn (and presented in Figure 16) accordingly with the relation between the solar radiation and electrical peak power profile, to ensure a high degree of accuracy.

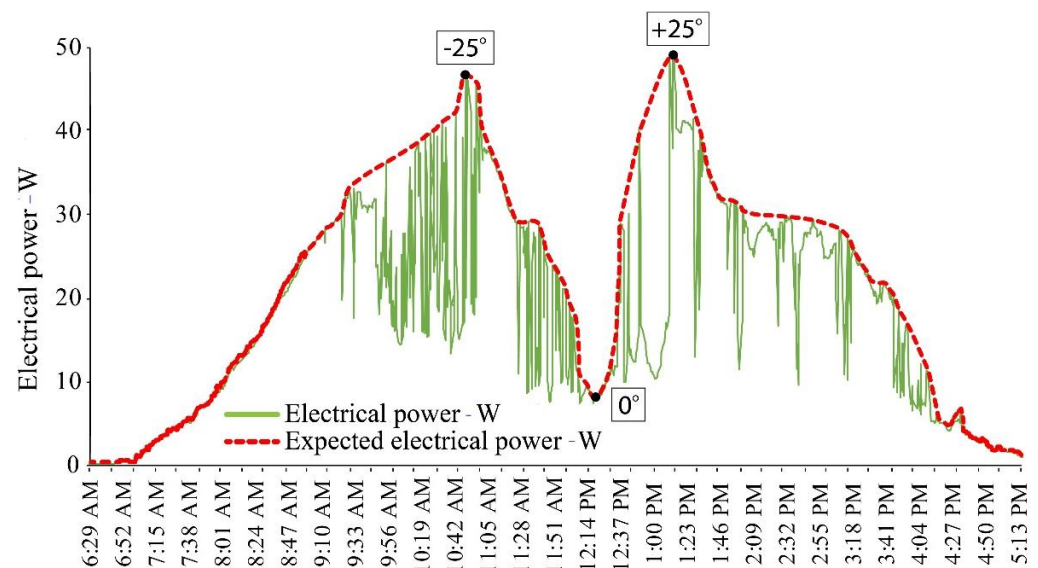


Figure 16. Transversal measured and expected electrical power on the 27th of September.

The angle of incidence of the sun with the vertical n-PERT bifacial cells is optimum (higher electrical peak power output) at 10:40 p.m. and 1:10 p.m., with the low peak power to be registered at normal incidence (around 12:15 a.m.). Moreover, the electrical peak efficiency at $\pm 25^\circ$ reached a value close to 10% (at 767 W/m^2) for an ambient air temperature of around 11°C , which shows the high dependence of any concentrating solar collectors to the solar radiation and thus to PV cell operating temperature.

Moreover, this phenomenon will allow the PV cells to operate at a lower temperature and, therefore, higher electrical peak efficiencies will be registered if compared with an east-west placement. Additionally, the ambient temperature on the 27th of September did not surpass 11°C which will allow the collector to be at a lower temperature, thus achieving a higher electrical peak power. In addition, at normal incidence the two images created by the reflector (two very strong focal lines) on both sides of the n-PERT bifacial PV cell might cause the cell not to be able to carry the current which increases the heat generation, thus lowering the electrical peak power. For lower transversal incidence angles θ_T , the two focal lines will be displaced and scattered, which enables the n-PERT bifacial PV cell to operate at optimum peak power.

By having an electrical peak power displaced from the highest incident radiation values (typically at normal incidence), the collector is able to achieve better performances, as the PV cell operating temperature will be lower, and the peak power will be higher for a longer period. Additionally, the PV cells will be exposed to a lower degradation enhancing the overall lifetime of concentrating solar collectors coupled with vertical n-PERT bifacial PV cells.

4. Conclusions

As any solar collector, the optimal operation period is during clear sky days (especially for concentrating solar collectors), nevertheless, the fact that the presented solar collector is characterized by a low-concentration ratio, allows the PV cells to capture not only direct light but also a small share of the diffuse light, which enhances its advantages when compared to standard PV modules.

The measurement results showed that the electrical peak efficiency reached 10%. For a perfect balance between the collector tilt and the projected solar altitude, an electrical peak power of 78 W/m^2 has been achieved.

The electrical IAM diagram showed to be extremely sensitive to the transversal incidence angles due to the specific placement of the receiver, which the electrical peak IAM (transversal direction) has reached a peak at $\pm 25^\circ$ of around 49.3 W/m^2 , which diverges

from the typical electrical peak IAM (at normal incidence, hence 0°) for flat solar collectors. The reflector tends to be less effective when the sun is directly above the collector, which leads to higher electrical power outputs whenever the incidence angles are bigger than 0° .

Therefore, the CPV solar collector has been successful at shifting the electrical peak power (typically at normal incidence) to higher incidence angles, which aids the electrical grid demand peak shaving (at hours of highest demand), by having the highest electric power production displaced from the highest intensity solar radiation during the day.

This CPV layout tends to be sensitive not only due to the tilt angle but also due to the azimuth (north-south or east-west placement in the test stand); therefore, it is required that the solar collector is precisely placed to achieve high electrical yields, in accordance with the latitude of the installation site. The authors' suggestion relies on taking the advantage of the vertical receiver placement, and therefore, the solar collector should be placed in a north-south (e.g., vertical) position to smooth the 'duck curve' as much as possible.

The higher costs of bifacial cells, when compared with standard c-Si solar cells, can be mitigated by employing longer reflectors and thus increasing the ability to capture a wider range of solar radiation (both direct and diffuse due to the lower concentration factor). Furthermore, the bifaciality of the presented PV cells allow them to capture more light (typically diffuse radiation) when the sun rays are being concentrated on one side of the bifacial PV cells.

Additionally, the PV cells are exposed to a lower degradation enhancing the overall lifetime of concentrating solar collectors coupled with vertical n-PERT bifacial PV cells.

However, the CPV solar collector can be improved, by employing a CPC reflector geometry as well as making a longer reflector to decrease frame shading.

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Nomenclature

Symbol	Description [Unit]
T_a	Ambient temperature [$^\circ\text{C}$]
G_b	Beam solar irradiance [W/m^2]
I_{mpp}	Current at maximum power point [A]
$\eta_{elect.}$	Electrical efficiency [%]
G	Global solar irradiance [W/m^2]
V_{oc}	Open-circuit voltage [V]
P_{mmp}	Power at maximum power point [W]

I_{sc}	Short-circuit current [A]
P_{el}	Specific electrical power output [W/m ²]
V_{mpp}	Voltage at maximum power point [V]
θ_c	Acceptance half-angle [°]
β	Collector tilt angle [°]
θ	Incidence angle [°]
θ_L	Longitudinal incidence angle [°]
θ_p	Projection angle [°]
γ_s	Solar azimuth angle [°]
ρ_{cell}	Solar reflectance [–]
τ_{cell}	Solar transmittance [–]
θ_z	Solar zenith angle [°]
θ_{NS}	South projection angle [°]
θ_T	Transversal incidence angle [°]
Subscripts	
CTM	cell-to-module
CPV	Concentrating Photovoltaic
c-Si	Crystalline Silicon
DNI	Direct Normal Irradiance
FF	Filling Factor
HCPV	High Concentrating Photovoltaic
IAM	Incidence Angle Modifier
LID	Light Induced Degradation
LCOE	Levelized Cost of Energy
LCPV	Low Concentrating Photovoltaic
PV	Photovoltaic
PERT	Passivated Emitter Rear Totally diffused

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