The Impacts of Tracking System Inaccuracy on CPV Module Power

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Keywords: tilt angle, azimuth angle, sun-tracking sensor, sun-tracking, concentrator photovoltaic module, solar energy

Abstract:

The accuracy and reliability of solar tracking greatly impacts the performance of concentrator photovoltaic modules (CPV). Thus, it is of utmost significance to know how deviations in tracking influence CPV module power. In this work, the positioning characteristics of CPV modules compared to the focus points were investigated. The performance of CPV modules mounted on a dual-axis tracking system was analysed as a function of their orientation and inclination. The actual experiment was carried out with CPV cells of 3 mm in diameter. By using a dual tracking system under real weather conditions, the module's position was gradually modified until the inclination differed by 5° relative to the optimal position of the focus point of the CPV module. The difference in inclination was established by the perfect perpendicularity to the Sun's rays. The results obtained specifically for CPV technology help determine the level of accuracy that solar tracking photovoltaic systems are required to have to keep the loss in power yield under a certain level. Moreover, this power yield loss also demonstrated that the performance insensitivity thresholds of the CPV modules did not depend on the directions of the alterations in azimuthal alignment. The novelty of the research lies in the fact that earlier, no information had been found regarding the tracking insensitivity point in CPV technologies. A further analysis was carried out to compare the yield of CPV to other, conventional photovoltaic technologies under real Central European climate conditions. It was shown that CPV needs a sun tracking accuracy of at least 0.5° in order to surpass the yield of other PV technologies. Besides providing an insight into the tracking error values of solar tracking sensor, it is believed that the results might facilitate the planning of solar tracking sensor investments as well as the economic calculations related to 3 mm cell diameter CPV system investments.

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Article The Impacts of Tracking System Inaccuracy on CPV Module Power

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Abstract: The accuracy and reliability of solar tracking greatly impacts the performance of concentrator photovoltaic modules (CPV). Thus, it is of utmost significance to know how deviations in tracking influence CPV module power. In this work, the positioning characteristics of CPV modules compared to the focus points were investigated. The performance of CPV modules mounted on a dual-axis tracking system was analysed as a function of their orientation and inclination. The actual experiment was carried out with CPV cells of 3 mm in diameter. By using a dual tracking system under real weather conditions, the module's position was gradually modified until the inclination differed by 5° relative to the optimal position of the focus point of the CPV module. The difference in inclination was established by the perfect perpendicularity to the Sun's rays. The results obtained specifically for CPV technology help determine the level of accuracy that solar tracking photovoltaic systems are required to have to keep the loss in power yield under a certain level. Moreover, this power yield loss also demonstrated that the performance insensitivity thresholds of the CPV modules did not depend on the directions of the alterations in azimuthal alignment. The novelty of the research lies in the fact that earlier, no information had been found regarding the tracking insensitivity point in CPV technologies. A further analysis was carried out to compare the yield of CPV to other, conventional photovoltaic technologies under real Central European climate conditions. It was shown that CPV needs a sun tracking accuracy of at least 0.5° in order to surpass the yield of other PV technologies. Besides providing an insight into the tracking error values of solar tracking sensors, it is believed that the results might facilitate the planning of solar tracking sensor investments as well as the economic calculations related to 3 mm cell diameter CPV system investments.

Keywords: solar energy; concentrator photovoltaic module; sun-tracking; sun-tracking sensor; azimuth angle; tilt angle

1. Introduction

1.1. Photovoltaic Technologies and Their Markets

In the global challenge of securing energy for the world's growing needs in a way that is sustainable, sufficiently diverse, and conducive to the worldwide efforts to reduce CO_2 emissions, renewable sources of energy have a key role to play [1]. One of the available solutions, generating energy by utilizing the energy of the Sun, satisfies all the above criteria, being both sustainable and environmentally friendly

as well as capable of ensuring the continuation of mankind's energy-intensive way of living [2–4]. Furthermore, solar energy is ubiquitous and can be converted into electric energy directly by using photovoltaic (PV) modules [5], in which PV cells convert solar irradiation into electricity, thus providing much needed energy to consumers with low levels of pollution and a high level of reliability.

The year 2018 was an important milestone in the spread of PV technology as the total capacity of installed PV systems surpassed 100 GW in that year, with the nominal power of the total global operating capacity exceeding 500 GW [6]. By 2019, the total aggregate operating capacity had reached 627 GW [7], with the top 10 nations being:

- 1. China (204.7 GW)
- 2. United States (75.9 GW)
- 3. Japan (63 GW)
- 4. Germany (49.2 GW)
- 5. India (42.8 GW)
- 6. Italy (20.8 GW)
- 7. Australia (14.6 GW)
- 8. United Kingdom (13.3 GW)
- 9. Republic of Korea (11.2 GW)
- 10. France (9.9 GW); [7,8].

According to certain forecasts, the nominal performance of the installed PV systems worldwide will amount to 1 297 GW by 2023. Experts also expect changes in the order of the most significant actors in the PV markets by 2023 [6], which will lead to the following sequence:

- 1. China, (448.1 GW)
- 2. United States, (132.4 GW)
- 3. India, (116.1 GW)
- 4. Japan, (82.4 GW)
- 5. Germany, (72.6 GW)
- 6. Australia, (45.2 GW)
- 7. Italy, (29.5 GW)
- 8. Spain, (25.4 GW)
- 9. Republic of Korea, (24.8 GW)
- 10. France (22.3 GW) [6].

The efficiency of commercially available monocrystalline (m-Si) and polycrystalline (p-Si) solar modules today reaches even 26.7% (m-Si) and 23.8% (p-Si), and their market share ranges between 85% and 90% thanks to their reliability. The amorphous silicon solar module (a-Si), which is a kind of thin-film solar module, can have an efficiency of 10.5%, but its market share is hard to estimate. Nevertheless, the total market share of all thin-film solar modules is approximately 10–15%. Despite this high efficiency currently attainable, in PV system installation it is more common to see less efficient crystalline (m-Si: 16–20%; p-Si 14–17%) and amorphous silicon solar modules (a-Si: 5–8%) because of their more favourable prices. Apart from the classic, most frequently used silicon-based modules, many other types are also used [9–11]. One of the main reasons for the limited efficiency of solar modules is the fact that the Sun's spectrum is much broader than the range of absorption of a semiconductor. A module made from a combination of various materials can absorb light much better than a simple one. Research and development is constantly ongoing not only in the fields of the silicon and thin-film technologies but also in those of the various materials, manufacturing processes, and innovative technologies. Such areas also include organic, bifacial, dye-sensitised or even perovskite solar technologies. One of the new directions among the currently available technologies is represented by concentrator photovoltaic modules (CPV), which can even reach an efficiency rate of over 40% under laboratory conditions [11–14]. At present, the CPV market is still quite little when compared to more traditional PV systems. Its total capacity was only about 70 MWp in 2014, while at the beginning of 2017 this figure was already around 380 MWp. [15].

The Characteristics of CPV Technology

As the popularity of the various technologies for solar photovoltaic energy conversion has greatly increased, it seems that it is traditional silicon PV systems that have managed to acquire a large market share, mainly thanks to their reliability and profitability as well as the support schemes introduced in many nations in the past decade [16–20]. However, silicon PV modules are known to be negatively influenced by hot climates, prevalent in regions characterised by intense solar radiation, in terms of both their reliability and performance. Consequently, it is necessary to explore new technologies in order to find ways to increase the general efficiency of energy conversion [12–14].

One of the possible solutions to increase efficiency in PV technology is to utilise sunlight, which is concentrated on high-efficiency solar cells by certain optical components [21,22]. Such systems (called CPV systems) have three principal parts: First of all, they contain special optics capable of reducing the amount of necessary photosensitive material and ensuring both technical [21] and environmental advantages [23]. Secondly, there is a tracking mechanism to maintain the optimal alignment of the rays of the Sun and the optics system. Finally, there are, of course, the PV cells. Unlike in other, traditional systems, the PV cells of CPV installations do not consist of conventional silicon wafers but so-called triple-junction (3J) converters [14,24,25]. Their higher cell efficiency, which is remarkable compared to silicon technologies, is based on the fact that each of their three layers transforms a specific narrow band of solar radiation into electric energy [21,26–28]. As for their operation at higher temperatures, they are far less sensitive than silicon cells, which makes them suitable for use in solar concentration systems. This can be easily proven by recent flash tests performed under concentrated light, showing a production cell conversion efficiency of up to 47.1% [14,27].

Nevertheless, high solar concentration resulting in high power densities is a challenge for reliability in the long-term. Thus, in order to guarantee long term usability, the cells are fixed on a metal surface to remove the surplus heat caused by the concentrated light not converted into electricity [29,30]. In terms of optics, CPV systems are normally based on the principles of reflection or refraction using shaped parabolas or Fresnel lenses, respectively. The optical concentration efficiencies of both of these solutions are remarkable, which is also attested by numerous researches, which have suggested that their optical performance could even reach a geometrical concentration ratio of more than 1000 suns currently. Nevertheless, due to the fact that Fresnel lenses are easier to produce and their costs are lower, they are more popular [14,31]. The tests in the manuscript were implemented using a CPV module equipped with Fresnel lenses with separate prism elements arranged in a concentric fashion on the superstrate.

Regarding Fresnel lenses, it is of paramount importance to emphasise that they can be manufactured relatively cheaply because they can be made of PolyMethylMethAcrylate (PMMA), which is a remarkable material for several reasons. Apart from being resistant to atmospheric agents and possessing great optical characteristics, it has high UV tolerance and excellent transmission performance in the wavelengths that are used in 3J solar cells. Nevertheless, it must be borne in mind that optical performance is influenced by a number of factors, such as the reflection on the surface, the optical transmission, the aperture to the focal length ratio, the draft angle and even the imperfections of manufacturing. Negative influences by unfavourable parameters lead to losses, which must be avoided, especially in the case of CPV systems if one wishes to obtain good general performance. The acceptance angle of the whole optical system is crucial for the choice of the tracking mechanism, and the higher the optical concentration ratio is, the higher the required tracking accuracy becomes [14,32–34].

As mentioned above, in the case of CPV systems, dependability is absolutely critical, which means that in order to be able to estimate their performance in the long run, statistical assessments have to be made [35]. With a view to avoiding inaccuracies caused by lacks in precision, such as the planarity of

the CPV chassis and misalignments in module mounting, it is advisable to use closed-loop control systems in the tracking motors, such as sun-sensors or encoders providing feedback concerning the absolute position and its alignment with the sun rays [14,36,37].

Unfortunately, CPV systems are only efficient in those regions of the world that are characterised by stable and intense Direct Normal Irradiance (DNI), such as high altitude areas and/or deserts (Figure 1) [14,38]. This is because of the fact that it is the direct solar rays, only a small portion of the solar radiation available, which the solar concentration in CPV technology allows to be utilised.



Figure 1. Direct Normal Irradiance in the world [39].

1.2. The Characteristics of PV Mounting Solutions and the Importance of Solar Tracking

The correct orientation, the right choice of the tilt angles as well as taking the shading effects into account are some of the most important factors for the efficient operation of any PV system. A wrongly adjusted tilt angle and/or improper orientation may result in the generation of less electric energy, on the one hand, and a longer payback period, on the other hand. It is indispensable to be aware of the local climatic conditions in the country concerned to be able to maximise the amount of energy generated annually. In Europe, the ideal tilt angle varies between 20° and 50° for PV systems oriented towards the south [40,41].

In order to increase the annual yield of PV systems, the role of solar tracking (single and dual axis) is becoming more and more significant. In 2018, the proportion of ground-mounted PV systems was around 70%. The reason for this is that in a large area it is possible to build PV systems of even up to several GW, whose technical operation and management is simpler than those of more scattered systems [6,42]. It is also likely that ground-mounted PV systems will remain dominant in the near future. Based on certain expert estimates, it can be inferred that in 2019, approximately 3–5% of all ground-mounted systems were equipped with some solar tracking technology, and reaching 10–15% within the next 10 years is an ambitious goal [6,43].

For the simulation of energy generation with solar tracking, several applications are available (e.g., Photovoltaic Geographical Information System (PVGIS), PVWatts Calculator, PV*SOL), which predict an increase in generated energy of 5–30% yearly compared to fixed systems, depending on the applied technology and the circumstances. In the case of actual energy production, these values range from 20% to 40% according to some sources [41,44–47], while others claim that, thanks to the enhanced efficiency of single- and dual-axis solar tracking solutions, the increase in generated energy is between 12–42%, depending on the mode of mounting and the actual site of installation [44,45,48–50].

In a European context, the research of Vokas et al. (2015) [46], who gathered a great amount of (>100 pieces) actual and detailed energy production measurement data from single- and dual-axis PV plants from eight different towns in Greece, provides an enlightening illustration. The results of their comparative studies showed an average difference of 34.8% between the average performances of fixed and dual-axis PV systems [46].

Here it is also worth mentioning the interesting fact that off-grid photovoltaic energy conversion with dual tracking systems is a more efficient solution from the perspective of energy generation than conventional, fixed PV systems. In those locations, for example, where public utilities are not available, the power supply of container systems could be ensured in a more optimised way by using tracking systems. Independent and efficient power supply could be of utmost importance in remote areas or in the event of disasters, where, for example, the supply of healthy drinking water may pose a challenge for public health [51–53].

1.3. The Implications of the Accuracy of Dual Tracking PV Systems for Energy Production

In an ideal case, using a solar tracker whose sensors monitor the orbit of the Sun, PV panel systems follow the sun with a great accuracy of less than 0.1 degree. By maintaining a right angle between the incoming solar radiation and the PV modules, it can maximise the current energy production [46,48,54]. According to evidence in the scientific literature, there are three key factors in achieving the highest efficiency possible:

- the configuration of the tracking axes [45,55]
- the configuration of the control systems [56]
- the optimisation of the moving fixtures [57].

At present, two types of solar tracking systems, which are widely discussed in the literature, are available (Figure 2):

- single axis solar tracking systems (rotating around a single axis) [58–62]
- dual axis tracking systems (rotating around two axes) [48,63–65].



Figure 2. Types of solar tracking solutions according to [66,67].

Although there is agreement among a number of scholars that dual axis tracking solutions are more efficient than single axis ones and they are also cost-effective if used in larger systems, the use of solar tracking devices is only advisable if the expenses associated with the equipment itself, its upkeep, and the energy consumed by the moving parts can be compensated for by the quantity of the generated electrical energy [44,45,48–50]. Another critical aspect of solar tracking solutions, which may be either

open- or closed loop systems depending on the applied control strategy and the manner of signal operation [50,54,68–70], is the control and tracking algorithms, which greatly influence precision and performance. Lee et al. (2009) [71] have studied a great number of algorithms and solar tracking systems of high accuracy and showed that the typical tracking error tolerance in these systems ranged between 0.0003° and 1°, but they also remarked that their investment costs were relatively high. On the other hand, there are also more affordable sensors and solar tracking systems, albeit with a minimum tracking error tolerance of 1.5° [72]. The solar tracking solutions available in the market are either simple generic or customised constructions (e.g., [73–82]). The more basic solutions are inaccurate; they are not able to find the real focus point, they do not set the modules into the ideal dawn position after sundown or at sunrise, thus the sun sensors can only do that later, with a significant time lag. This, of course, affects power generation adversely. Another problem with the simpler solutions is the constant search for the brightest point in the sky, which means an endless search for direction in cloudy weather. This results in an excess load for the sun tracking motors, the faster wear of mechanical parts and less actual power generation since the unnecessary operation of the motors requires extra energy. The customised constructions have mainly been created for CPV systems, where there is constant focusing. Compared to the more basic constructions these are capable of precise sun tracking, but several problems have not been solved yet (e.g., the fine constant movement of the motors for precision, cloud protection).

By investigating the relationships between tracking inaccuracy and performance in traditional PV technologies, Nsengiyumva et al. (2018) [54] found that, regardless of the cardinal direction, an inaccuracy of 10° in solar tracking caused a mere 1.5% decrease in performance. Contrary to that, however, a three-year-long series of measurements carried out in Hungary detected a more complex relationship [67]. In the latter research project, three different PV technologies (m-Si; p-Si; a-Si) were compared by means of a dual axis solar tracking mounting system. The incoming sunlight reaching the module surfaces was set with an accuracy of 3 mm using a CPV module, hereafter referred to as focus point (FP). The study examined the changes in performance as a function of deviation from the focus point. The results showed that the performance changes in the m-Si, p-Si, and a-Si modules were influenced not only by the extent of the deviation from the focus point but also by its direction. The changes in the energy generation of the crystalline PV modules caused by directional changes were nearly identical, so average values could be established. For tracking uncertainties of up to 10° occurring when testing the a-Si technology, the characteristics were almost identical to those of the crystalline modules, but above that value a-Si technology responded to changes in direction more sensitively. The performance proved to be the least sensitive to deviation in the north-south direction, while the most sensitive ones were the north-west, south-west, south-east, and north-east directions. The research also established that in the case of a deviation of less than 3° compared to the focus point no decrease in performance occurs, regardless of the direction of the deviation or the given PV technology. These results constitute an important aspect for the planning of the accuracy of solar tracking systems and/or sensors. The insensitivity point of 3°, determined by this study, may also have economic implications by highlighting the question, whether in the design of solar tracking devices the 3° threshold should be surpassed, and if yes, to what extent. In addition, the research findings may be useful regarding the planning of solar tracking systems and the calculations of investment costs and returns in the case of m-Si, p-Si, and a-Si PV systems [67].

The novelty of this research lies in the fact that earlier, no information had been found regarding the tracking insensitivity point in CPV technologies. Our preliminary measurements indicated that CPV technology was extremely sensitive to changes in orientation. Thus, the present study was first aimed at exploring this aspect, which may provide important information for future investments too. Secondly, we compared the yield of CPV technology to other, conventional PV technologies as a function of sun tracking accuracy.

2. Material and Methods

2.1. Test Location and Description of the Study

For the purpose of our tests, a dual-axis tracking system with a CPV module was used under real meteorological conditions (Table 1, Figure 3). The experiments were conducted at the PV measuring station of the University of Pannonia in Hungary, Keszthely (longitude: 17.26609°, latitude: 46.76750°, altitude 108 m a.s.l.), and measurements were taken on thirty different days during the summers of 2018, 2019, and 2020.



Figure 3. The photovoltaic (PV) testing station of the University of Pannonia in Hungary, Keszthely (1. CPV module, 2. OTT TRH relative humidity sensor; 3. DS-2 Sonic anemometer, 4. EMS 11 Silicon PV detector, 5. photosensors, 6. Eppley Black and White pyranometer, 7. a-Si module, 8. p-Si module, 9. Hukseflux LP02 pyranometers, 10. m-Si module, 11. manual/automatic tracking control unit, 12. HYTE-ANA-1735 humidity module [measuring air humidity], 13. Pt 100 sensor [measuring air temperature]; Blue dot: Pt 100 sensor [measuring the temperature of the air inside the CPV module]; Red dot: Pt 100 sensor [measuring the CPV module's cell temperature at the rear].

The voltage and current calibration was done by using a professional multimeter (Voltcraft VC607) (Conrad Electronic SE, Wernberg-Köblitz, Germany), verified on an LT1021 (Linear Technology Corporation, Milpitas, USA) precision reference. The current (A) and the voltage (V) of the PV modules were optimised with oscillation true maximum point seeking (TMPS) devices, which allowed the

manual checking of the maximum power points of the PV modules for optimal measurement precision (Figure 4). Also, the V and A values could be directly measured without any loss in the TMPS devices.

Table 1. Technical specifications of the concentrator photovoltaic (CPV) module. (standard test conditions: air mass 1.5; cell temperature 25 °C; irradiance = 850 W/m^2).

Module Type	CPV
Model	CX-75-III
Nominal power (Pmax) (W)	75
Performance tolerance (%)	±5%
MPP current (Imp) (A)	0.55
MPP voltage (Vmp) (V)	135
Open circuit voltage (Voc) (V)	150
Short circuit current (Isc) (A)	0.64
Efficiency (%)	27.2
Temperature Coefficient (%/°C)	0.15
Cell diameter (mm)	3
Cell units per module (piece)	98
Concentrator type	Point focusing silicone on glass Fresnel lense
Cell type	Triple junction solar cell
Cooling system	Passive cooling with copper



Figure 4. The configuration of PV module measuring station 'A'.

For this study, technical and environmental data were gathered by using a CR1000 measurement (Campbell Scientific, Inc., Logan, UT, USA) and a control data logger, a GB HOBO (Onset Computer Corporation, Bourne, USA) four-channel analogue data logger, a PicoLog 1216 (Pico Technology, St Neots, United Kingdom) acquisition system, and a PicoLog 1012 (Pico Technology, St Neots,

United Kingdom) data acquisition system (Figures 4 and 5). With the help of these instruments, all measured data were recorded in a PC every second (PicoLog) or every 10 s (CR1000).



Figure 5. The configuration of PV module measuring station 'B'.

The intensity of the radiation was measured with two devices: a Hukseflux LP02 pyranometer (Hukseflux Thermal Sensors B.V., Delft, The Netherlands) and an Eppley Black and White Model 4–48 Pyranometer (The Eppley Laboratory, Inc., Newport, RI, USA), while for the global horizontal irradiation an EMS 11 Silicon PV detector (Energy XPRT, Brno, Czech Republic) was used (Figures 4 and 6). The air humidity was recorded with a HYTE-ANA-1735 (B+B Thermo-Technik GmbH, Donaueschingen, Germany) meter and by an OTT TRH relative humidity sensor (OTT Hydromet GmbH, Kempten, Germany), while the angles of the photovoltaic modules and the pyranometers were measured using a digital angle gauge (Figure 4).

The PV modules were positioned with the help of two linear actuators and using a handheld remote control (both for horizontal and/or vertical control) to perform a series of tests. The visible focus point (FP) of the CPV solar module was used to monitor the precise adjustment to the sun (Figure 6), i.e., where the sun rays are perpendicular to the PV modules in the optimal case. The measurements taken at the FP position served as a reference to calculate the power loss as a function of the inaccuracy in solar tracking. This means that the technology-specific performance losses caused by imprecise sun tracking could be measured relative to the optimal position.

Concerning temperature data, the temperatures of the PV module and of the ambient air were monitored with Pt 100 sensors (Conrad Electronic SE, Wernberg-Köblitz, Germany) coupled with PicoLog devices. The whole measuring circuit was calibrated with the help of a digital LM 35-based precision thermometer (B+B Thermo-Technik GmbH, Donaueschingen, Germany). Since the temperatures of the PV modules stayed stable during the tests, the temperature values were meant for information solely in this study (Figures 7 and 8) (see chapter "2.2. Data Processing and Analysis"). For the visualisation of the temperature characteristics of the CPV module, a FLIR E60BX infrared

camera (FLIR Commercial Systems Inc., Nashua, NH, USA) was applied (Figures 7 and 8). An emission coefficient of 0.9 was used for these measurements following [83]. Figures 7 and 8 show some of the infrared images taken at measuring stations 'A' and 'B', which were used at the same location and times during summer of 2018, 2019, and 2020 (Figures 4 and 5).



(a)



(b)



Figure 6. By using CPV cells, the inaccuracy in alignment to the sun becomes easily visible (**a**) precise setting, (**b**) inaccurate setting, (**c**) inaccurate setting.



(a)



Figure 7. The back of CPV module 'A' in visible radiation (a) and in infrared radiation (b).

2.2. Processing and Analysis of the Obtained Data

The data were collected on thirty different days between 11:00 am and 1:30 pm during the summers of 2018, 2019, and 2020. Measurements were always made according to two methods, (i) continuously (every second, station 'A' (Figure 4)) and (ii) at 10-s intervals (station 'B' Figure 5). To measure the irradiance and the PV performance, the inclination of the PV module was modified towards the north, north-west, west, south-west, south, south-east, east, and north-east. It means that in order to find

the performance insensitivity threshold for CPV technology, irradiance and module performance measurements were made between the FP (Figure 6a) and solar tracking deviations of 1°, 3°, and 5° in 0.2–0.5-degree increments in every direction. The performance values could be directly measured with no loss in the TMPS devices.



(a)



Figure 8. The back of CPV module 'B' in visible radiation (a) and in infrared radiation (b).

The orientations, radiation, and performance for all angles of the PV module were measured relative to the FP of the CPV solar cells, serving as a starting position (Figure 6a). The measurement of

the performance output lasted for 10 s for each position, while it took 1–3 s to switch to the next one. A waiting time of approximately 6 s also occurred because of the switching of the measuring devices. Thanks to the fact that the starting point for all the measurements was the FP, the effects of the changes in environmental conditions could be excluded (e.g., changes in PV module temperatures) (Figure 6a).

During the experiments, the measurements were taken 30 times altogether for each direction, then the averages of the obtained data were calculated and compared to the relative standard deviation (CV%). As it is well known, relative standard deviation ranging from 0 to 10% indicates homogeneity, medium variability ranges between 10.1 and 20%, from 20.1 to 30% the variability is strong, while deviations of more than 30.1% signal high heterogeneity [52]. Regarding the measurements in this research, an excellent result was achieved, as the relative standard deviation of the averaged data remained below 1%. As for systematic mistakes, they are difficult to spot because of their nature and they do not increase the deviation in measurements. Nevertheless, this problem can be mitigated by high measuring precision and the appropriate calibration of the instruments. The data were processed, analysed, and assessed with the help of Matlab (version: R2017a, Natick, MA, USA), Microsoft Excel (version: 2016, Redmond, WA, USA), PicoScope (version: R5.23.0, St Neots, United Kingdom) and SPSS Statistics (version: 24, Armonk, NY, USA).

2.3. Yield Calculations and Comparison to Other Technologies

We then performed analysis and yield calculations for real radiation conditions using routine DNI and global radiation measurements from the measurement platform of the University of Natural Resources and Life Sciences (BOKU) in Vienna (48° 14′ N and 16° 19′ E, 266 m a.s.l.), which had been performed at 1-min intervals since August 2017 using a first-class CHP1 pyrheliometer (Kipp & Zonen, Campbell Scientific, Inc., Logan, UT, USA) mounted on a sun tracker and a second-class MS-802 global radiation pyranometer (EKO Instruments B.V., San Jose, CA, USA), respectively. The instruments are regularly calibrated using the ARAD network measurement station situated also in Vienna at a distance of about 1 km [84]. For our analysis, the data from 2018 were used. The yearly DNI and global radiation sums were calculated. The radiation (IRR_{INC}) incident on inclined south-oriented PV modules (3 technologies m-Si, p-Si, and a-Si) was calculated using the following Equation (1) by adding the direct beam component DIR_{INC}, the diffuse irradiance incident on the inclined plane, and the ground reflected radiation reflected towards the PV modules.

$$IRR_{INC} = DIR_{INC} + DIFF_{INC} + IRR_{REF}$$
(1)

where the direct irradiance is equal to

$$DIR_{INC} = DNI \times COS (angle_{norm})$$
(2)

where $angle_{norm}$ is the angle to the normal of the inclined planes and DIR_{INC} is the direct beam radiation incident on the inclined planes.

The diffuse radiation $DIFF_{INC}$ incident on the inclined plane is calculated using the following Equation (3):

$$DIFF_{INC} = DIFF_{HOR} \times 0.5 \times (1 + \cos\beta), \tag{3}$$

where β is the inclination of the PV module and DIFF_{HOR} is the diffuse irradiance on a horizontal plane.

$$DIFF_{HOR} = GLOB - DNI \times \cos(SZA), \tag{4}$$

where GLOB is the global irradiance incident on a horizontal plane and SZA is the solar zenith angle. We then need to calculate the ground reflected radiation IRR_REF using the following Equation (5):

$$IRR_{REF} = A \times 0.5 \times (1 - \cos\beta) \times GLOB,$$
(5)

where A is the albedo.

We assumed in our simulations an albedo value of 0.2 and made calculations for south-oriented PV modules with inclinations of 30, 45, and 60 degrees. We also simulated the yield of a-Si, m-Si, and p-Si modules mounted on sun trackers. At the end, the impact of the uncertainty of the solar trackers on the performance and the efficiency of the modules was taken into account (Table 2). The uncertainty of the solar tracking device on the yield of the respective PV modules was calculated by multiplying DNI with a correction factor K_{suntrack} (Equation [6]) taking into account the inaccuracy of the sun tracker.

$$K_{suntrack} = (1 - err_{track}/100), \tag{6}$$

where $\operatorname{err}_{\operatorname{track}}$ is the decrease in performance for the given tracking uncertainty (shown in Table 2). By adding the diffuse component (see Equation (1)) to $\operatorname{K}_{\operatorname{suntrack}}$ x DNI, the yield Y was calculated using following Equation (7):

$$Y = AR \times r \times IRR_{INC} \times PR.$$
(7)

Y = Energy yield (kWh)

AR = total solar module area (m²)

r = solar module efficiency (%)

IRR_{INC} = Incident solar radiation on tilted modules (shadings not included)

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

The performance ratio was set to 1 and calculations were performed for 1 m^2 . The efficiencies of these flat plate solar modules were taken from Table 2 and the incident solar irradiance IRR_{INN} was calculated using equations 1 to 5. It has to be mentioned in passing that for the calculation of yield for CPV IRR_{INC} is equal to DNI.

Table 2. The efficiency of CPV a-Si, m-Si, and p-Si PV modules and the average impact of sun tracking uncertainties of 0.5°, 1°, 5°, and 10° on the performance of these modules (values for a-Si, m-Si, and p-Si taken from [67]).

Module Type	CPV	a-Si	m-Si	p-Si
Module efficiency (%)	27.2%	5.3%	14.4%	13.7%
Impact of 0.5° sun tracking uncertainty on performance reduction, average (%)	11	0		
Impact of 1° sun tracking uncertainty on performance reduction, average (%)	82	0		
Impact of 5° sun tracking uncertainty on performance reduction, average (%)	100	0.88		
Impact of 10° sun tracking uncertainty on performance reduction, average (%)	100	2.5		

3. Results

3.1. The Performance Insensitivity Threshold of CPV Technology as a Function of Azimuthal Direction

Unlike in the case of m-Si, p-Si, and a-Si technologies, no performance insensitivity threshold was found for CPV technology based on the results of our measurements. When the changes occurred in the same direction around the FP, the deviations in performance remained the same. Figure 9 illustrates this phenomenon for an easier understanding of the effects of inaccuracy in solar tracking. A mere 1° deviation compared to the FP resulted in only 18% of the original performance of the CPV module, while in the case of a difference of 1.5° the energy generation stopped completely in the examined 3 mm diameter CPV cells. In contrast to this, in the case of the more conventional technologies, no variation in performance occurred as a function of the deviation compared to the FP when the angle of deviation was below 3°. For a more precise description of the results and the relationships, a rational polynomial regression model (Table 3, Figure 9) was created.



Figure 9. Changes in CPV performance as a result of 0.5° modifications in direction compared to the FP (CPV cell diameter: 3 mm).

Table 3. The effect of directional changes on CPV performance (x = change in orientation (°); f(x) = percentage value of the performance compared to the FP) (CPV cell diameter: 3 mm).

Description	Equation	Numerical Results for Modelling	R-Square
The effect of directional changes on CPV performance	$\begin{aligned} f(x) &= (p1 \times x^3 + p2 \times x^2 + p3 \times x + p4) / \\ &(x^3 + q1 \times x^2 + q2 \times x + q3) \end{aligned}$	p1 = -2232 p2 = 6789 p3 = -6679 p4 = 2272 q1 = 4912 q2 = -6212 q3 = 2268	0.999

To guarantee the reproducibility of the results of our experiments, it was our goal to publish them in great detail. In addition, they may facilitate the planning processes of solar tracking sensor investments and the calculations of the expenses related to the investments and their operation as well as their return in the context of CPV systems. Also, the same results offer great insight into the tracking error values of solar tracking sensors.

3.2. Rational Polynomial Regression Models for Dual Axis Solar Tracking CPV Systems with Tracking Deviations of $0-1.5^{\circ}$ Relative to the FP

A rational polynomial regression model (Table 3, Figure 9) was produced from the results displayed in Figure 9 by using the Matlab software.

Although other regression methods were also considered (exponential, logarithmic, multivariable, and quadratic) for the analysis of the data, the closest fit with the highest R-squared value was delivered by the polynomial regression model. The regression relationship between the deviation from the FP and the performance of the solar module can be best described by a cubic rational polynomial ($R^2 = 0.999$). The curve clearly shows that the diagram can be divided into two polynomial sections. The first section is from the FP to a deviation of 0.5°, where the performance expressed as 100% decreases to

89%. The second section, starting at deviations greater than 0.5°, already shows considerable losses in performance (Figure 10).



Figure 10. Changes in the performance of CPV technology as a result of 0.1° directional changes compared to the focus point (FP) based on the created rational polynomial regression model (CPV cell diameter: 3 mm).

Applying the rational polynomial regression models, equations were developed (Table 3) that define the performance of a CPV module as a function of inaccuracies in solar tracking up to 1.5°. These equations and the values of changes in direction can be used for estimating the performance changes of this technology applying dual-axis solar tracking systems. The acquired R-square values for the CPV performance displayed a nearly perfect fit (Table 3).

3.3. The Comparison of CPV Yield to a-Si, m-Si, and p-Si Technologies for Real Conditions

The Calculation of Radiation Sums

Using the routine measurements of DNI and global radiation data from the year 2018, taken at 1-min intervals, the yearly sums for 2018 as well as the monthly sums for January and July 2018 of DNI and IRR_{INC} incident on planes with inclinations of 30° , 45° , and 60° were calculated using equations 1 to 4. In addition, the maximum possible irradiance (sum of DNI and DIFF_{INC}) was calculated for a plane continuously tracking the sun (that means with an optimal position to the sun). Figure 11 shows, among others, that the south-oriented plane with a 30° inclination receives a yearly radiation sum that is higher than the yearly DNI sum.

Figure 12 shows the monthly yields of January and July 2018 calculated by using equations 1 to 6. January was chosen to simulate typical winter conditions, while the month of July represents those of summer. The yield of CPV is much higher than the yield of the other technologies in both months, even when compared to the other sun tracker-mounted PV modules. Thus, an inaccuracy of the sun tracking of up to 0.5 degree can guarantee a higher yield. An inaccuracy of 1 degree, however, has serious consequences on the yield and leads to yield losses of approximately 80%. That still corresponds to the yield of July of the 60 degree inclined a-Si PV modules. In January, however, the yield is even lower.



Figure 11. The yearly sum of Direct Normal Irradiance (DNI), direct beam, and diffuse irradiance incident on an inclined plane that is tracking the sun (max), radiation incident on a plane with 30 degree inclination (glob30°), with 45 degree inclination (glob45°), and with 60 degree inclination (glob60°).



Figure 12. Calculated yields for January and July 2018 for 4 different technologies: CPV, a-Si, m-Si, and p-Si. The results are shown for sun tracking systems (CPV, a-Si track, m-Si track, p-Si track) and for fixed PV modules with inclinations of 30 degrees (a-Si 30°, m-Si 30°, and p-Si 30°) of 45 degrees (a-Si 45°, m-Si 45°, and p-Si 45°) and 60 degrees (a-Si 60°, m-Si 60°, and p-Si 60°). In addition, the yields of a CPV module mounted on a solar tracker with a 0.5° tracking uncertainty (CPV 0.5° uncert) and with a 1° tracking inaccuracy (CPV 1° uncert.) are shown.

The yearly yield (Figure 13) is very similar to the results for January. CPV technology delivers—when compared to the other technologies—the highest annual yield. A CPV system will still be profitable even with a sun tracking inaccuracy of 0.5 degrees but this will not be the case with an uncertainty of 1 degree.





Figure 13. The yearly yields calculated for 2018 for 4 different technologies (CPV, a-SI, m-Si, and p-Si). The results are shown for sun tracking systems (CPV, a-SI track, m-Si track, and p-Si track) and for fixed PV modules with inclinations of 30 degrees (a-Si 30°, m-Si 30°, and p-Si 30°) of 45 degrees (a-Si 45°, m-Si 45°, and p-Si 45°) and 60 degrees (a-Si 60°, m-Si 60° and p-Si 60°). In addition, the yields of a CPV module mounted on a sun tracker with a 0.5° tracking uncertainty (CPV 0.5° uncert.) and with a 1° tracking uncertainty (CPV 1° uncert.) are shown.

In Figure 14, the impact of a solar tracker uncertainty on the yield of the 4 technologies CPV, a-Si, m-Si, and p-Si is shown. While the three conventional PV technologies (a-Si, m-Si, and p-Si) do not show any decrease in yield up to an uncertainty of 5 degrees, the CPV yield drops very rapidly. Even for inaccuracies of up to 10 degrees the conventional PV modules show only a slight decrease (not higher than 3%).



Figure 14. The yearly yields calculated for 2018 for 4 different technologies (CPV, a-Si, m-Si, and p-Si). The results are shown for sun tracking systems (CPV, a-Si track, m-Si track, and p-Si track) as a function of different tracking uncertainties (0.5°, 1°, 5°, and 10°).

4. Discussion

As suggested by the scientific literature [54], solar tracking system devices enjoy great popularity, and their performance remains over 98.5% of their full tracking efficiency even if their aim is off by 10°. However, the discrepancies in PV performance indicate a considerable dependence on the azimuthal direction in the case of traditional PV modules. Earlier test results [67] also showed that there was no variation as a function of the deviation compared to FP in the examined conventional PV technologies when the angle of variance stayed below 3°. This result can be an important aspect to be considered in designing the accuracy of solar tracking systems / sensors. The insensitivity point of 3°, determined by the research, also has economic considerations, as it points out the issue whether in designing a solar tracking device, the threshold of 3° should be exceeded or not, and if yes, to what extent. Earlier, no information had been found regarding the tracking insensitivity point in CPV technologies, but our measurements indicated that CPV technology was extremely sensitive to changes in orientation. Contrary to the above, in the case of a CPV module, the variation in performance could be divided into two polynomial sections. The first part was from FP up to a deviation of 0.5°, where the 100% performance associated with FP decreased to 89%, while in the second section, over 0.5°, a much more significant difference was detected, indicating a considerable drop in performance. In the case of a deviation of 1.5°, the energy generation stopped entirely in the examined 3 mm diameter CPV cells. The research results can provide important help with the technology-specific design of sun tracking systems and the calculations of the return indicators of investments in the case of m-Si, p-Si, a-Si and CPV-based PV systems too.

Our results suggest that it is the densely populated regions of our planet where the performance per unit of area of the PV system matters most, since in such locations, the suitable area available for the construction of PV systems is not unlimited. In order to boost the yearly specific yield (generated power per unit of area) the role of solar tracking (single and dual axis), the right tilt angle and direction are coming more and more to the fore. These features can even allow an annual increase of 30–40% in energy generation compared to optimally placed, south facing PV systems on the same area. For the maximisation of the yearly extra power yield it is important to choose a tracking system with the appropriate accuracy in the case of dual axis PV systems, because less precise equipment may reduce the annual energy production.

5. Conclusions

In this study, the positioning features of concentrator photovoltaic modules were examined and compared to the focus point using a dual axis tracking system under actual meteorological conditions. Based on the findings of the experiments, it was established that the performance insensitivity threshold of the CPV module did not depend on the direction of the changes.

The simulations of the monthly and annual yields of CPV systems, compared to conventional technologies under Central European climatic conditions, show that CPV technology (due to its higher efficiency) may deliver yields that are approximately 17% higher than those of conventional PV modules mounted on sun trackers and almost 30% higher than those of fixed PV modules.

A solar tracking uncertainty of 0.5 degree will lead to a yield decrease in the case of CPV systems, but their yield will still be higher compared to that of the other technologies. A 1° uncertainty will result in a serious reduction in yield, which is below the energy yield obtained with other PV systems.

The measurement and simulation results highlight the importance of solar tracking accuracy in CPV systems. A wrongly selected solar tracking system or one degraded (i.e., with decreased tracking accuracy) by use impacts the energy generation–and, consequently, also the payback features–of the PV system significantly. Thus, based on the results of this study, it can be stated that a CPV power plant can only operate efficiently if it is coupled with a solar tracking system of adequate accuracy.

In the future, the scope of our research will be extended to bifacial PV modules. Preliminary measurements suggest that this technology is less sensitive to changes in orientation, and determining its insensitivity features could prove to be of great importance from the perspective of future investments.

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Abbreviations

The following abbreviations are used in this manuscript:

А	Ground albedo
AR	Total solar panel area [m ²]
a-Si	Amorphous silicon
CPV	Concentrator photovoltaic
DIFF _{HOR}	Diffuse irradiance incident on horizonal plane [W/m ²]
DIFFINC	Diffuse radiation incident on tilted plane [W/m ²]
DIR _{INC}	Direct radiation incident on tilted plane [W/m ²]
DNI	Direct Normal Irradiation [W/m ²]
err _{track}	Reduction of performance due to a sun tracking uncertainty
G _{HOR}	Global radiation on a horizontal plane [W/m ²]
G _{INC}	Global radiation incident on tilted plane [W/m ²]
G _{REF}	Irradiance reflected by the ground towards the PV module [W/m ²]
K _{suntrack}	Correction factor which takes into account the sun tracker uncertainty
m-Si	Monocrystalline
angle _{norm}	Angle to the normal of the tilted plane [degree]
PMMA	PolyMethylMethAcrylate
PR	Performance ratio (coefficient for losses)
p-Si	Polycrystalline
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
r	Solar module efficiency [%]
R ²	R-Square
SZA	Solar zenith angle [degre]
TMPS	True maximum point seeking
Y	Energy yield [kwh]
3J	Triple-junction
β	Inclination of the PV module [degree]

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