

Field measurement of the wind ~~Flow Downstream~~ flow downstream of a ~~Parabolic Trough Solar Collector Array~~ parabolic trough solar collector array

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Abstract.

Wake effects are often simplified in wind-resistant design for solar facilities. As dense layout and plant scale increases, inner solar units are exposed to upstream wakes, facing distinct wind patterns and turbulence. This paper provides insights into wake turbulence inside a solar power plant using field measurement wind data from Utility-scale concentrated solar power (CSP) plants comprise multiple collector arrays, where wake interactions between rows influence the dynamic wind loading on supporting structures. These wake effects have primarily been investigated through wind-tunnel experiments and numerical simulations, while field measurements remain scarce. This study examines the mean flow and turbulence characteristics downstream of the first three rows of parabolic trough collectors at the Nevada Solar One ~~–~~ The field measurement provides the wind conditions at three heights (7 m, 5 m, and (NSO) plant. Sonic anemometer measurements at 3.5 m) for inflow wind, wake after outmost 3 rows and the solar tracker is 5 m width and 8 m length installed 2.79 m above ground. Mean wind profiles and turbulence statistics are presented and compared between different rows using ensemble 30-minutes average values. The aim is to investigate the one-point integral statistics of the mean flow and turbulence as well as turbulence power spectra for both upstream and downstream of the rows. A mean wind speed decrease of over 70% is observed after the 1st, 2nd, and 3rd rows compared 5 and 7 m were analysed under near-perpendicular inflow conditions to assess the shielding effects of upstream rows. Mean wind speeds decreased by 21–80% relative to the inflow ~~;~~ with close wake speeds at each height. The main wind direction shift occurs behind the 1st row and a partial recovery is observed in subsequent rows reference speed at 7 m, with the largest reduction occurring downstream of the first row. Wind direction deviations were also most pronounced behind the first row, followed by partial recovery downstream. The standard deviations of the streamwise (u and w components show only small changes between rows while the w component at 5 m height which is behind the solar mirror increases consistently downstream) and lateral (v) velocity components decreased at lower heights but increased above the collectors, with relatively little variation between successive rows. In contrast, vertical velocity fluctuations increased by 30–100% and continued to develop downstream. Skewness and kurtosis revealed persistent departures from Gaussian behaviour within the wakes, indicating that the apparent rapid adjustment of horizontal velocity fluctuations does not extend

to all turbulence statistics. These findings suggest the onset of flow adjustment to the aerodynamic resistance of the collector array, although the measurements cannot establish whether equilibrium is reached within the first three rows. The results highlight the limitation of overlooking wake changes in the wind-resistant design and provide quantified wake turbulence to help avoid potential wind damage and reduce over-design for the inner solar units.

that mean-flow sheltering does not necessarily imply reduced turbulence, with implications for the aerodynamic loading of downstream collectors.

1 Introduction

Utility-scale photovoltaic plants are becoming substantially larger: among U. S. solar power plants are growing in size. Among US photovoltaic (PV) projects exceeding 5 MW, mean capacity doubled the mean capacity increased from approximately 36 MW AC for plants commissioned in 2010–2019 to 73 MW in 2020–2023, reaching 84 MW in 2023 [1]. Although PV dominates the solar energy market, concentrated solar power (CSP) offers the advantage of thermal energy storage [2]. The increasing scale of both solar power plants and individual solar units [3] makes solar installations and their individual structures [3] raises important questions about their interaction with the atmospheric boundary layer and internal wind modifications inside of the power plant is not negligible for its device. Wind design standards often neglect row-to-row wake effects, even though upstream rows alter. Solar panels and parabolic trough collectors are exposed to substantial wind loads, while upstream rows can shelter downstream structures by modifying the mean flow and turbulence experienced by interior units. As the capacity of solar power plants, their impact on the power grid and the stability and continuity of power generation becomes important. The main solar technologies are solar photovoltaic (PV) and concentrated solar power (CSP). PV accounts for over 90% of the solar market [2], while CSP can offer stable and continuous power supply with its thermal storage systems. Even though PV takes up more market, CSP has potential for a future high capacity power plant [2] and becomes competitive with conventional energy infrastructures in the past five years. However, these intra-array wake effects are not systematically accounted for in wind-load design.

The primary component of PV or CSP systems is a large surface, thin-shell mirror or tracker. Such structures are exposed to high wind loads and wind-related damage. In most solar power plants, the first row can shield the subsequent rows from strong wind. However, it is unclear whether the shielding effects also apply to turbulence dynamic load and few researches investigate the wind and turbulence modification by solar rows. There is a gap between quantifying and analysing the turbulence in wake the corresponding row response. The shielding effects of first row on Numerical simulations and wind-tunnel experiments have demonstrated substantial reductions in mean wind speed is studied by Williams [4], the mean wind speed distribution in horizontal panel in the solar array and the wake speed after each row are provided, but the turbulence changes are not investigated in this study. The wake mean wind speed changes are also studied by An and Azadeh [5, 6]. In Yang's paper [7], they present the mean wind speed distribution and wind power spectrain vertical direction after each rows using numerical simulation and the drag and pitching moment coefficients are also presented. Marano [8] took more turbulence statistics into the studies, the downstream of solar panels and collectors, with wake characteristics depending on collector geometry and tilt angle [4, 5, 6]. Beyond mean-flow sheltering, collector wakes also modify turbulence characteristics, including velocity

power spectra, with implications for aerodynamic forces and moments [7, 8]. These findings indicate that reductions in mean wind speed distribution, standard deviation and the power spectra of u and w in vertical direction after each rows using numerical simulation are presented and its relationship with drag coefficient is analysed. alone cannot fully characterise the wind conditions experienced by downstream collectors. However, most existing investigations rely on numerical simulations or wind-tunnel experiments, while full-scale field measurements remain scarce.

All above researches are based on numerical simulation, few studies on wind turbulence in solar arrays have been carried out using field measurements. Furthermore, most of the field measurements using one single wind mast which only provide the inflow wind information [9, 10, 11, 12]. This results in limited comparison between inflow wind and concurrent wake wind behind solar rows based on measured data. Egerer et al. [13] performed a three-year field measurement at NSO, using one outside mast and three inside masts installed after multiple solar rows, providing both inflow wind and concurrent wake information. Structural response are also included in this dataset. Further studies based on this field measurement dataset have been carried out by Stanislawski et al. [14], who investigated the relationship between Previous field studies have often relied on a single meteorological mast, limiting their ability to capture the spatial evolution of the flow across successive collector rows [9, 10, 11, 12]. The field measurement campaign at the Nevada Solar One (NSO) plant provides an opportunity to address this limitation, with simultaneous measurements of the undisturbed inflow and wakes downstream of three collector rows [13]. Previous analyses of this dataset have examined wind-induced torsion of solar collectors and incident wind and tilt angle. Wan et al. [15] examined inflow wind data from the outside mast and proposed a new power spectrum model. Egerer et al. (2024) [16] studied collector torsion, inflow wind spectra and selected wake characteristics, including wind direction, turbulence kinetic energy, turbulence intensity, and length scale in the wake data. There is still a lack of investigation into high-order turbulence statistical moments, which are essential for gaining deep insight into turbulence after different solar rows. intensity, turbulent kinetic energy and integral length scales [14, 15, 16]. However, the downstream evolution of the velocity fluctuations and higher-order turbulence statistics across successive collector rows remains insufficiently characterised.

The aim of this paper is using field measurement wind data to analyse the flow statistics behind the first row of parabolic mirror of a CSP power plant. Specifically, the paper focuses on comparing the mean wind profile and high-order statistical moments of the inflow wind and the wake behind different solar rows, with the inflow wind perpendicular to the solar array. Internal wind variations must be considered in the design process as the scale of solar plant increases. This paper quantifies turbulence modification inside a parabolic trough solar collector array based on This study investigates the mean flow and integral turbulence statistics downstream of the first three rows of parabolic trough collectors at NSO under near-perpendicular inflow conditions. The analysis compares mean wind speed, wind direction, flow inclination angle, and the standard deviation, skewness and kurtosis of the three velocity components between the undisturbed inflow and successive collector wakes. Particular attention is given to whether the shielding of the mean flow is accompanied by similar changes in turbulence and to identifying evidence of downstream flow adjustment. The findings provide field-based methodology, providing valuable input for wind-resistant design for solar facilities. The implications are to avoid potential structural risks and reduce possible over-design of internal solar units by applying wake statistics in the design of solar power plants.

In this paper, the wind speed in the wake behind different solar rows shows similar values, while wind direction deviation from the inflow recovers after the first row. The standard deviation

of the w component indicates an increase in the intensity of the turbulence in the wake, especially behind the solar mirrors. Skewness and kurtosis results reveal a further departure from Gaussian turbulence compared to the inflow wind, evidence of intra-array wake effects relevant to the aerodynamic design of downstream collectors.

The paper is organized as follows: Section 2 presents the location of NSO, the instrumentation of field measurements, and the data processing and selection. Section 3 presents the results for mean wind profile, standard deviation, skewness and kurtosis, and power spectra of the three wind components at three measured heights for both inflow and wake after different organised as follows. Section 2 describes the measurement campaign and data processing. Section 3 presents the mean wind profiles and turbulence statistics downstream of successive collector rows. The results show that most changes in mean wind speed and horizontal velocity fluctuations occur downstream of the first row, whereas vertical fluctuations continue to evolve further downstream. Skewness and kurtosis reveal persistent departures from Gaussian behaviour, suggesting that turbulence adjustment remains incomplete within the first three rows.

2 Instrumentation and Methods

2.1 Field measurement

The dataset used in this paper is from field measurements at Nevada Solar One present study uses field measurement data from NSO [13]. Figure 1 shows the location and the layout of NSO, as well as details of the measurement campaign. NSO is a concentrated solar power (CSP) CSP plant with a nominal capacity of 72 MW, located in Boulder City, in Nevada, USA, at coordinates $(35.8^\circ N, -114.983^\circ E)$. There are two main mountain chains are located approximately 2.5 km northwest and 3.5 km east of NSO. The terrain within 2.5 km is relatively flat and the flat terrain extends up to 10 km to the south.

The field measurement took place

Measurements were conducted at the first, second, third and forth rows at four rows of solar collectors along the western edge of NSO. The right bottom panel of fig.1 shows the location of the outside mast and inside masts. Figure 2 shows the measurement layout is shown in the bottom-right panel of Figure 1, while Figure 2 provides a side view of the solar arrays and the masts. There is one outside mast in the western direction instrumented masts. A reference mast (hereafter referred to as the outside mast) was positioned 30 m away from west of the solar arrays and, while three additional masts (inside masts) were installed downstream of rows 1, 2, and 3 to characterize the wake flow under westerly wind conditions. Each mast was equipped with three sonic anemometers are installed at at heights of 3.5, 5, 7 m heights and one cup anemometer is installed at 15 m height. There are 3 inside mast which work as wake mast when the wind comes from western side. Three wake masts are installed after the row 1, row 2 and row 3. There are also three sonic anemometers installed at the same heights as outside mast but no cup anemometer. There are also sensors installed in rows 1, 2 and 4. An inclinometer sensor is used to record the 7.5 m, measuring the along-wind (u), cross-wind (v), and vertical (w) velocity components, as well as sonic temperature, at a sampling frequency of 20 Hz. The outside mast was additionally equipped with a Thies First Class cup anemometer at 15 m, sampling at 1 Hz. The dynamic tilt of the solar collector. For the collectors was recorded using an inclinometer.

The sonic anemometer configuration changed during the measurement campaign. On the outside mast, one Thies First Class cup anemometer is installed and it works with a sampling frequency of 1 Hz. One a Gill WindMaster Pro and two Gill WindMaster are was installed at 7.5 m, while Gill WindMaster anemometers were used at 5 m and 3.5 m. The anemometer at 5 m is anemometer was added in February 2022 and the anemometer at, and the 3.5 m have been changed to anemometer was replaced by a Gill WindMaster HS in November 2022

and ~~subsequently by a Campbell CSAT3 after November 2022. The anemometer installed at~~
~~On inside mast 1 at, the 3.5 m height has been changed to anemometer was replaced by~~
~~a Gill WindMaster HS in April 2022 and Campbell CSAT-3 a Campbell CSAT3 in November~~
~~2022. The anemometer installed at corresponding anemometer on inside mast 2 at 3.5 m~~
~~height has been changed to Campbell CSAT-3 in November 2022. There are no changes in the~~
~~anemometer at inside mast 3. All the sonic anemometer collect wind data with a sampling~~
~~frequency of 20 Hz besides the cup anemometer at the outside mast. There are also sensors~~
~~for measuring the torque moment was also replaced by a Campbell CSAT3 in November 2022,~~
~~whereas the instrumentation on inside mast 3 remained unchanged. Additional sensors recorded~~
~~structural responses, including torque, bending moments, displacement, and acceleration, but~~
~~these response data are not used in this study, we will not provide further illustration or analysis~~
~~of these response data measurements are not considered in the present study.~~

Section 2.1 shows the recording ~~Figure 3 shows the working~~ period of the outside wind mast, 3 wake masts and tilt angle inclinometer. Outside mast ~~works worked~~ from 2021 November to 2023 March, while the inside masts ~~record the wind collected wind data~~ during 2021 November to 2022 April and 2022 November to 2023 March. The tile angle data ~~is provided was collected~~ from 2022 December to 2023 March.

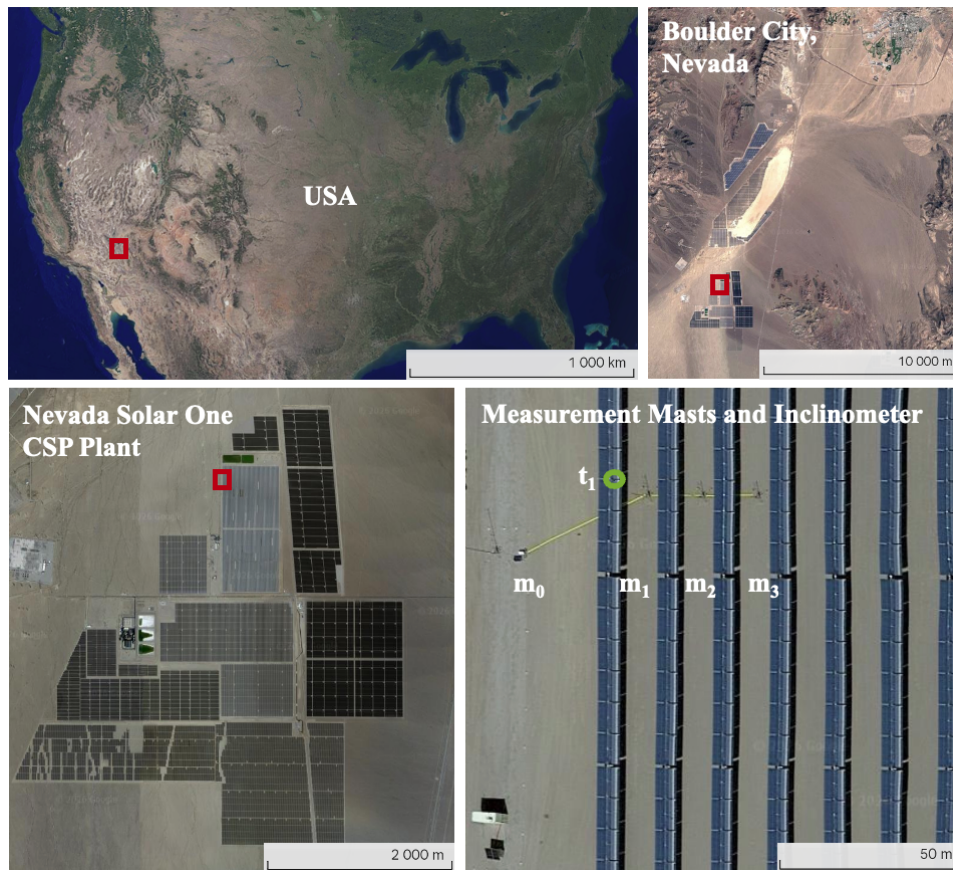


Figure 1. Satellite view of NSO and ~~sketch of~~ field measurements. The upper panels show the location of NSO. The bottom left panel shows the position of the field measurements at NSO, while the bottom right panel shows the location of the wind masts and their spatial relation to the solar arrays.

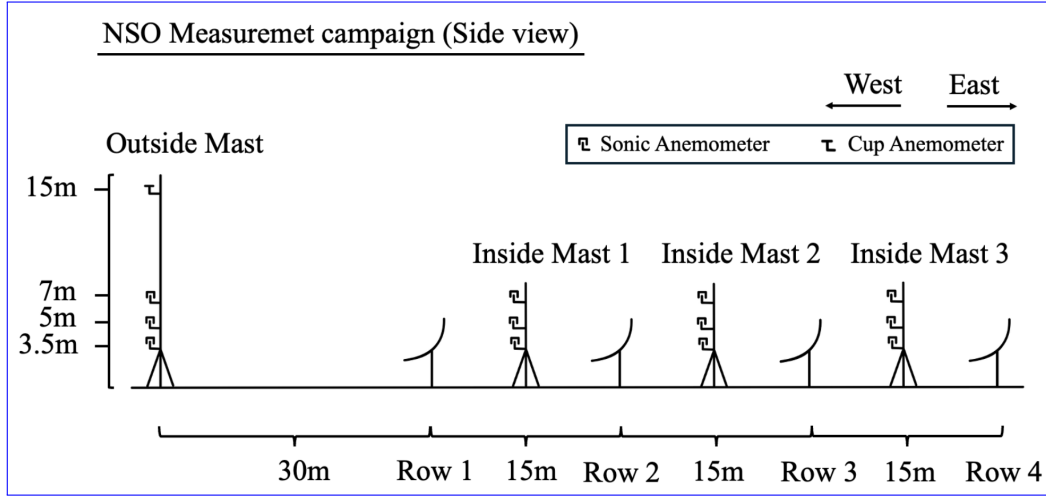


Figure 2. Side view of wind mast installation, showing the spatial relation between wind masts and solar arrays, as well as the configuration of anemometers.

2.2 Data overview and selection

Figure 4 The stationarity of the time series was assessed using first- and second-order stationarity tests based on moving means and moving standard deviations, respectively. First-order stationarity was considered satisfied when the relative deviation between the moving 900-s mean and the overall 30-min mean did not exceed 20%. Similarly, second-order stationarity was considered satisfied when the relative deviation between the moving 900-s standard deviation and the overall

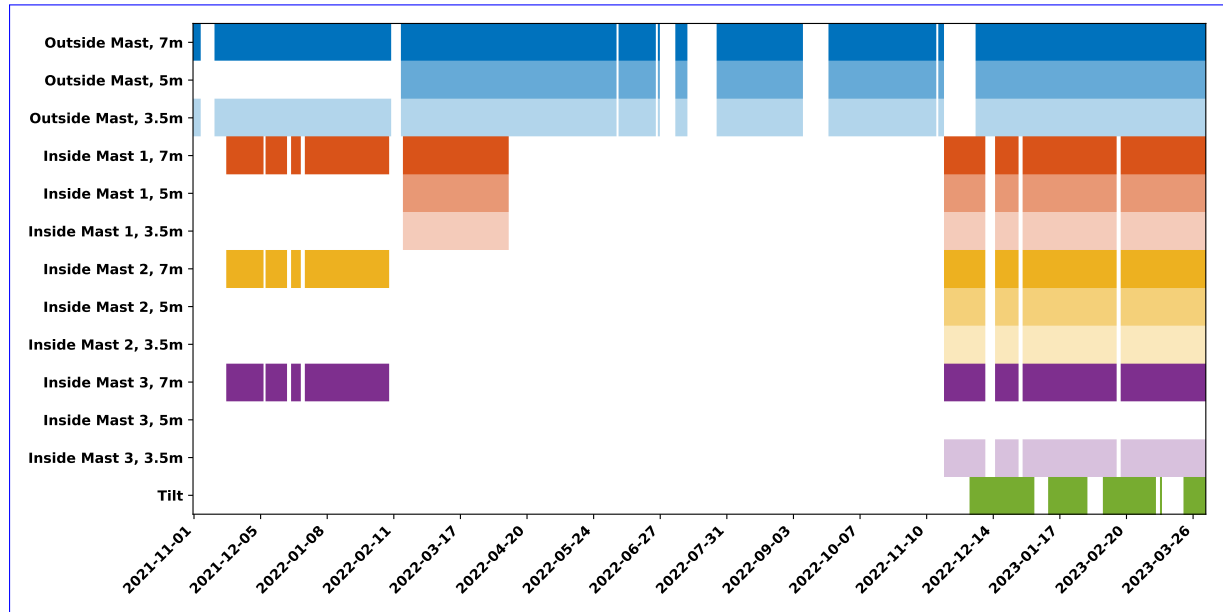


Figure 3. Time distribution of various data collected during the field measurements from November 2022 to March 2023. The along-wind u , cross-wind v and vertical w wind components and the sonic temperature are collected at outside and inside masts. The tilt angle of space frame is collected with inelinometer.

30-min standard deviation did not exceed 40% [15].

The atmospheric stability was evaluated using the non-dimensional stability parameter, $\zeta = z/L$, where z is the measurement height and L is the Obukhov length [17], defined as

$$L = -\frac{\bar{\theta} u_*^3}{\kappa g \overline{w'\theta'}} \quad (1)$$

where $\bar{\theta}$ is the mean virtual potential temperature, approximated by the sonic temperature; u_* is the friction velocity; $\kappa \approx 0.4$ is the von Kármán constant; g is the acceleration due to gravity; and $\overline{w'\theta'}$ is the turbulent kinematic virtual potential temperature flux. Based on ζ , atmospheric conditions were classified as unstable ($\zeta \leq -0.1$), neutral ($-0.1 < \zeta < 0.1$), or stable ($\zeta \geq 0.1$).

Figure 4 provides an overview of atmospheric stability and its relationship with wind speed, wind direction, time, and solar irradiance. Figure 5 shows the wind rose for the outside wind using the wind data from the outside mast, while the middle and right panels illustrate the differences in prevailing wind direction between daytime and nighttime. All samples were taken from the outside mast at a height of 7 m. Atmospheric stability is classified as unstable $\zeta \leq -0.1$, stable $\zeta \geq 0.1$, or neutral $-0.1 < \zeta < 0.1$.

As shown in fig.4 indicates when Figure 4 indicates that when the wind speed exceeds 6 m s^{-1} , the wind 6 m s^{-1} , the atmospheric stability can be considered as neutral. The results neutral more than 80% of the time. Figure 4 and Figure 5 show clear differences in prevailing wind direction and atmospheric stability between day and night. During daytime, the prevailing wind is north, and unstable conditions are more frequent due to strong irradiance. At night, the prevailing wind shifts to south, and The prevailing wind direction shifts from northerly during the day to southerly at night. Daytime solar heating promotes unstable atmospheric stratification, whereas stable conditions are more common due to low or no irradiance. Similar 180° reversals in wind direction between daytime and nighttime have been observed in other valleys characterized by strong diurnal wind cycles [18]. For solar energy infrastructure, these reversals suggest that wind-loading conditions are governed by the combined effects of tilt angle, mean wind direction, mean wind speed, and turbulence characteristics above and within the array. While fatigue loading is not directly assessed in this study, the observed variability is relevant to its future evaluation in wind-engineering applications.

3 Results and discussion

2.1 Mean wind profile

A systematic analysis which used to quantify the modifications from the solar rows to the inflow is performed in this section. This systematic analysis The analysis presented in Section 3 is based on an ensemble of samples when the inflow wind measured at at 79 30-minute measurement periods from November 2022 and April 2023, selected according to the inflow conditions measured at 7 m height of outside wind mastsatisfies following conditions: neutral atmospheric condition m height on the outside meteorological mast. The selection criteria were neutral atmospheric stability, stationary flow, a mean wind speed over exceeding 3 m s^{-1} , westerly wind (wind direction from and a wind direction between 240° to and 290°). Considering that. Periods without collector tilt-angle measurements were excluded, as the tilt angle of the CSP affects the wake, only samples with available tilt-angle data are included in the systematic analysis. This results in influences the wake characteristics. For each period, the mean wind direction and flow inclination angle were determined from the original velocity components before applying the double-rotation method. The velocity components were then transformed into a mean-flow-aligned

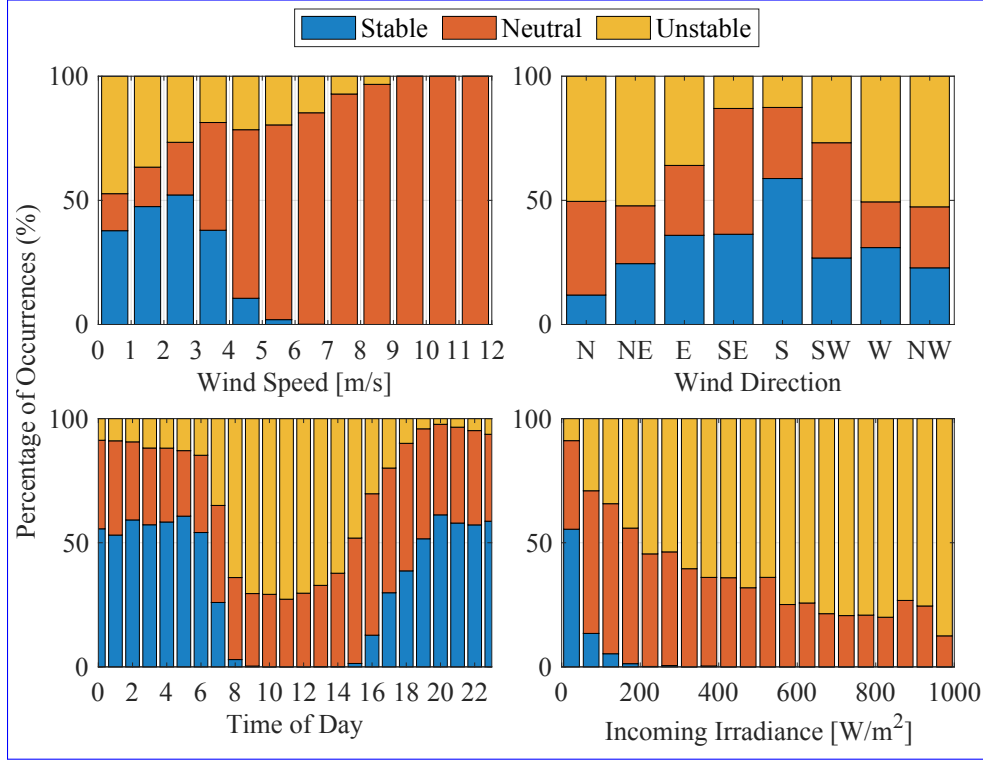


Figure 4. Distribution of atmospheric stability against wind speed, wind direction, time of the day, and incoming irradiance. The stable, neutral and unstable cases are selected using [the](#) non-dimensional stability parameter ζ ; $\zeta \geq 0.1$; $-0.1 < \zeta \leq 0.1$; $\zeta < -0.1$.

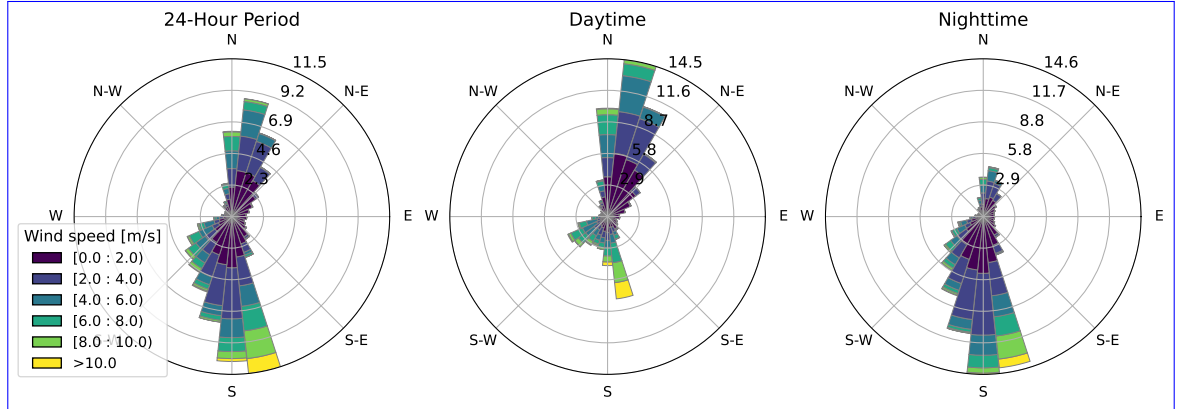


Figure 5. Wind rose from outside mast at 7 m height. The left panel shows all the samples from November 2022 to March 2023 which is 20930 samples. The middle and right panels show the daytime and nighttime wind roses, respectively.

[coordinate system, such that \$\bar{v} = \bar{w} = 0\$. Mean wind-speed profiles and higher-order turbulence statistics were calculated for each period and subsequently ensemble-averaged over the 79 samples from November 2022 and April 2023 being used for the analysis of mean wind profiles, higher statistical moments, and power spectra. Each sample represents a 30-minute averaged wind process. It should be noted that wind data from the 5-m height on the selected periods. At](#)

inside mast 3 are missing from the field measurement campaign. The wind data at 7 m and measurements at 5 m height were unavailable. The values at 3.5 m are connected linearly to illustrate changes and trends, but this does not represent 5 m and 7 m are therefore connected by straight lines for visualisation purposes only and should not be interpreted as representing the actual wind conditions at 5 m for inside mast 3 intermediate heights.

3 Results and discussion

3.1 Mean wind profile

Figure 6 shows the normalized mean wind speed, wind direction deviation, and wind incidence deviation which indicate the changes of mean wind profile from inflow wind to wake wind. The blue lines of these figures indicate the wind from outside mast. The wind direction deviation and the wind incidence deviation incidence angle deviation of undisturbed inflow is closed to 0° for all height which means the inflow wind direction keep constant for all heights and the wind is blowing directly perpendicular to the ground surface. And the mean wind speed decreases closer to the ground, which is consistent with the logarithmic law little directional variation with height and an approximately horizontal inflow.

The left panel of fig.6 shows the wind speed changes in the solar array wake. The wind speed has deficit in the wake wind data after three different row and the most wind speed deficit happened at 5 and Figure 6 shows the variation in mean wind speed downstream of the three collector rows. Pronounced wind-speed deficits are observed within the array, particularly at heights of 3.5 m height which remain and 5 m, where the mean wind speed decreases to approximately 20% of the inflow wind speed. This deficit is due to the blocking of the solar mirror which is located 2.79 m above the ground with 5 m width. Even through the wind mast at measured at 7 m height m. This reduction is primarily attributed to flow blockage by the parabolic mirrors. Yang et al. [7] reported a wind-speed reduction of approximately 70% relative to the free-stream velocity in numerical simulations with comparable collector spacing, showing

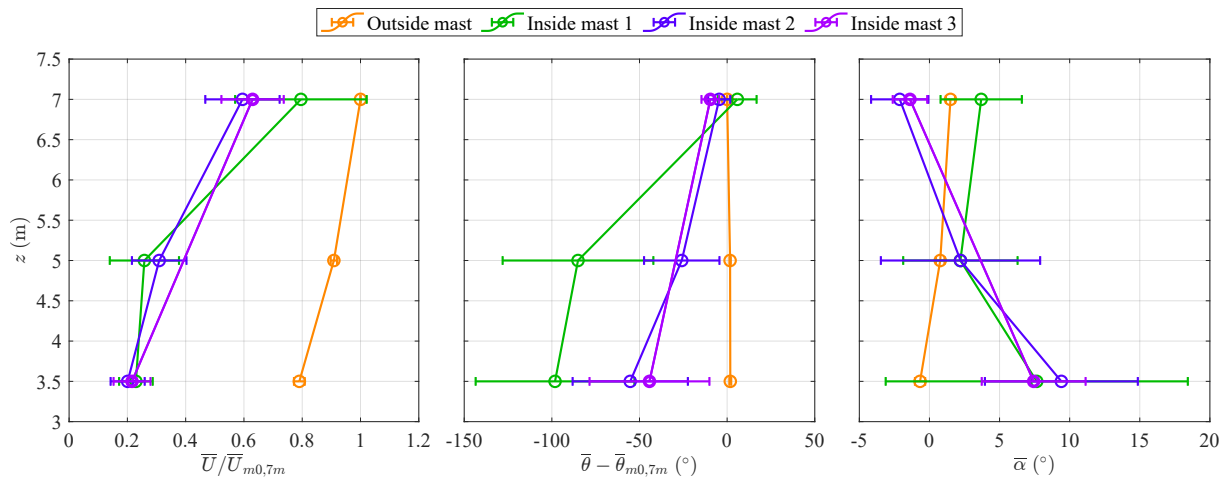


Figure 6. Mean wind profile which includes normalized mean wind velocity, wind direction deviation and incidence angle. The left panel shows normalized mean wind velocity which is the velocity from different mast masts at different heights divided by the velocity from outside mast at 7 m height. The middle panel shows the wind direction deviation which is the wind direction from different mast at different heights minus the velocity from outside mast at 7 m height. The right panel shows the incidence angle.

reasonable agreement with the substantial velocity deficits observed downstream of the first row in the present measurements.

Although the measurement height of 7 m is above the solar mirror, there is still wind speed deficit, this indicates the energy supply from the high-wind to the low-wind area which explain why the wind speed at 7 m height after 2 and 3 row show further wind speed decrease. It can be noted that the wind speed at all heights are similar for inside mast 2 and inside mast 3, which are located after the collectors, a reduction in mean wind speed is also observed at this height, indicating that the wake extends above the array. The additional reductions downstream of the second and third solar array rows. This indicates that the wind speed decreases primarily after rows may be associated with turbulent momentum exchange between the higher-speed flow above the array and the lower-speed flow within the wakes. Overall, the largest wind-speed reduction occurs downstream of the first row, while subsequent rows experience less reduction. This finding demonstrates the additional reductions across subsequent rows are relatively small. This suggests that the first row provides a shielding effect for the subsequent rows, which implies similar wind speeds can be assumed for the inner solar rows during wind-resistant design downstream collectors, resulting in broadly similar mean wind conditions within the array. From a design perspective, these findings suggest that a common mean wind-speed specification may be appropriate for interior collectors under near-perpendicular inflow conditions.

The middle panel of fig.6 shows the wind direction changes. The wind direction at Figure 6 shows the variation in mean wind direction across the collector rows. At 7 m height for all inside masts shows almost no change compared with inflow wind. Wind direction shifts m height, the wind direction remains largely unchanged relative to the upstream conditions at all three inside masts. In contrast, substantial directional deviations are observed at 5 m and 3.5 m heights, mainly due to the blocking effect of the solar mirrors. Compared to and 5 m, where the flow is likely influenced by the blockage and deflection caused by the parabolic mirrors. At inside mast 1 which shows a, the wind direction deviates by approximately -100° change in wind direction at 5 m and 3.5 m, inside mast 2 and inside mast 3 exhibit wind direction recovery, with changes reduced to from the inflow direction, whereas smaller deviations of around -50° . This recovery in wind direction is due to are observed at inside masts 2 and 3. This partial recovery towards the upstream wind direction suggests progressive flow realignment downstream, potentially driven by entrainment and turbulent mixing between the wake and surrounding undisturbed inflow wind, which help the wake gradually realign with the original wind direction as it moves downstream. The blocking effect of the first row causes the large deflection, while subsequent rows have less impact, allowing the wind direction to partially recover. collector wakes and the surrounding flow.

A strong incidence angle deviation is observed. The mean flow inclination angle exhibits the largest deviation from the horizontal at 3.5 m height which can reach m height, reaching approximately 10° . While the incidence angle deviation is under, compared with less than 5° . The Strong deviation at 3.5 m indicates stronger wake effects and turbulence caused by both solar mirror and compressing effect of ground surface. at other measurement heights. This indicates more pronounced vertical flow deflection in the lower part of the wake, potentially resulting from interactions between the flow, the ground and the parabolic trough collectors. Previous studies have shown that the aerodynamic lift forces on parabolic trough collectors are sensitive to the orientation of the incoming wind, particularly the wind-incidence and yaw angles [19, 9]. The observed flow deflection may therefore influence the aerodynamic loading on downstream collectors.

3.2 High-order statistics moments

~~The standard deviation of three wind component~~

3.2 *Integral turbulence statistics*

~~Figure 7 presents the standard deviations of the three wind velocity components (u , v and w are shown in fig.7. The standard deviation of u and v show similar trend. At 3.5 m and 5 m heights, the standard deviations decrease slightly by about). The streamwise and lateral components exhibit similar trends relative to the undisturbed inflow, decreasing by approximately 30% and 10% at 3.5 and 5 m, respectively, respectively. In contrast, while increasing by 21–28% at 7 m height, the standard deviations increase by 21%–28%. Since standard deviation reflects turbulence intensity, this indicates that turbulence increases above the solar mirrors, likely due to flow separation as the wind passes over the mirrors. The decrease in turbulence at 3.5 m.~~

~~Standard deviation of the wind velocity components u , v and w for the systematic analysis. The figure displays the median of 79 samples that meet the criteria of natural atmospheric stability, stationary flow, minimum wind speed of 3 ms^{-1} and western wind direction (240° – 290°).~~

~~It is worth noting that the standard deviation m. These differences may reflect flow sheltering within the array and enhanced turbulence near the upper edge of the collector wakes. Where measurements are available, the standard deviations of u and v at all heights shows similar values and distributions for inside mast 1, 2, and 3. This indicates that the standard deviation does not change significantly in the wake after different rows. The main changes for u and v in turbulence occurs after the first row, where the inflow is initially disturbed by the solar mirrors. After this initial changes, the turbulence reaches a relatively steady state due to mixing and redistribution of energy in the wake. vary little between the three inside masts, indicating that the largest changes occur downstream of the first collector row.~~

~~The In contrast, the standard deviation of the vertical component (w increases by 30%–100% at all heights, indicating turbulence enhance in the w component throughout the wake at all heights. The largest increase occurs) increases by 30–100% across the measured heights, with the largest increase at 5 m height, suggesting that the solar mirrors generate turbulence in the vertical direction behind the mirror. Additionally, the standard deviation of w for inside mast 2 shows an increasing trend compared to inside mast . At this height, vertical fluctuations increase further between inside masts 1 , especially at 5 m height. Unfortunately, wind data at 5 m for and 2, although missing measurements at inside mast 3 is missing, making it difficult to determine whether this increasing trend will continue or not prevent assessment of their subsequent development. A greater increase in vertical than streamwise velocity fluctuations was also reported by Marano [8]. These differences highlight the three-dimensional and anisotropic nature of turbulence within the collector wakes, consistent with observations in bridge near-wake [20]. The pronounced changes downstream of the first row, followed by a more gradual evolution, suggest the onset of flow adjustment to the aerodynamic resistance of the collector array, similar to the response of a turbulent boundary layer to a change in surface roughness. However, the available data indicate that continued development of vertical velocity fluctuations suggests that this adjustment may not be complete by the third row. Further analysis of the standard deviation of w consistently increases as the inflow wind passes through the first and second rows.~~

~~velocity power spectra is needed to establish how the observed changes in turbulence are distributed across frequencies.~~

~~Figure 8 shows presents the skewness and kurtosis of three wind components at three heights. Skewness and kurtosis are key high-order statistic moments to check whether the wind turbulence follows Gaussian process. Even the inflow wind measured from the outside mast already show departure from Gaussian turbulence, the wake exhibits further deviation from~~

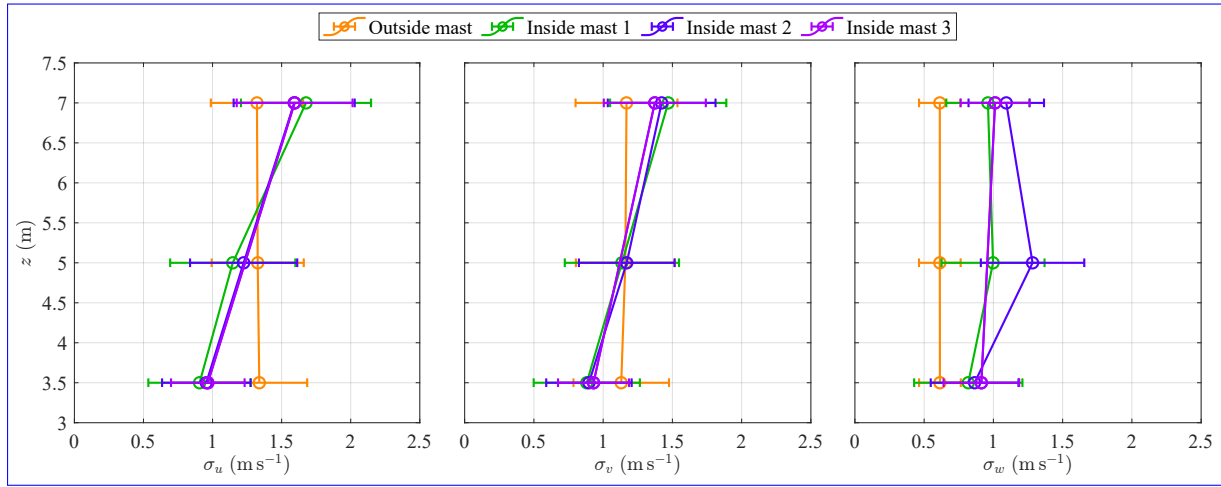


Figure 7. Skewness and Kurtosis Standard deviation of the wind velocity components u , v and w . The figure displays for the median of 106 samples that meet the criteria of natural atmospheric stability, stationary flow, minimum wind speed of 3 m s^{-1} and western wind direction (240° – 290°) systematic analysis.

Gaussian turbulence. Skewness of the three wind velocity components (u , v and w) at the three measurement heights. Although the undisturbed inflow already departs from a Gaussian distribution, these deviations are generally more pronounced within the collector wakes. At 3.5 m height is close to 0, the skewness of u remains comparable to that of inflow wind but has more variability than the inflow wind. For the wake form inside mast 1, the skewness even shows slight revert to 0, especially for the inflow but exhibits greater variability. Downstream of the first row, it shifts slightly towards zero, particularly at 5 m heights. The skewness of v and w wind components show max departure components exhibit their largest negative skewness at 5 m height which reach -0.4 to -0.5 m, reaching approximately -0.4 to -0.5 . While the skewness of v wind component have similar value for all the inside mast, remains similar across the three inside masts, that of w wind component show increased departure from inside mast 1 to inside mast 3, especially for becomes increasingly negative downstream, particularly at 3.5 m height m. Overall, the u component exhibits the most positive skewness, indicating a tendency for weaker wind events in the wake. In contrast, skewness is predominantly positive for u and negative for v and w components show the most negative skewness, suggesting a higher likelihood of extreme fluctuations in the lateral and vertical wind directions in the wake than the inflow wind.

The kurtosis of u and v wind components show increased kurtosis as the height decreases, with little change observed increases towards the ground, while remaining close to the inflow values at 7 m compared to the inflow wind. The wake data behind three rows for u and v components are very similar. In contrast, the w component displays a different pattern: exhibits a different trend: its kurtosis decreases by approximately 0.4 at 7 m, remains similar with comparable to the inflow at 5 m, and increases at 3.5 m height. For most heights except m. Except for u and v at 7 m the kurtosis values for all three wind components are close to m, kurtosis values approach 4, indicating the presence of sudden, sharp wind gusts and lulls rather than smooth, predictable flow suggests that wake is more prone to intermittent, extreme deviations from the mean value exceeding the Gaussian reference value of 3. This suggests heavier-tailed velocity distributions

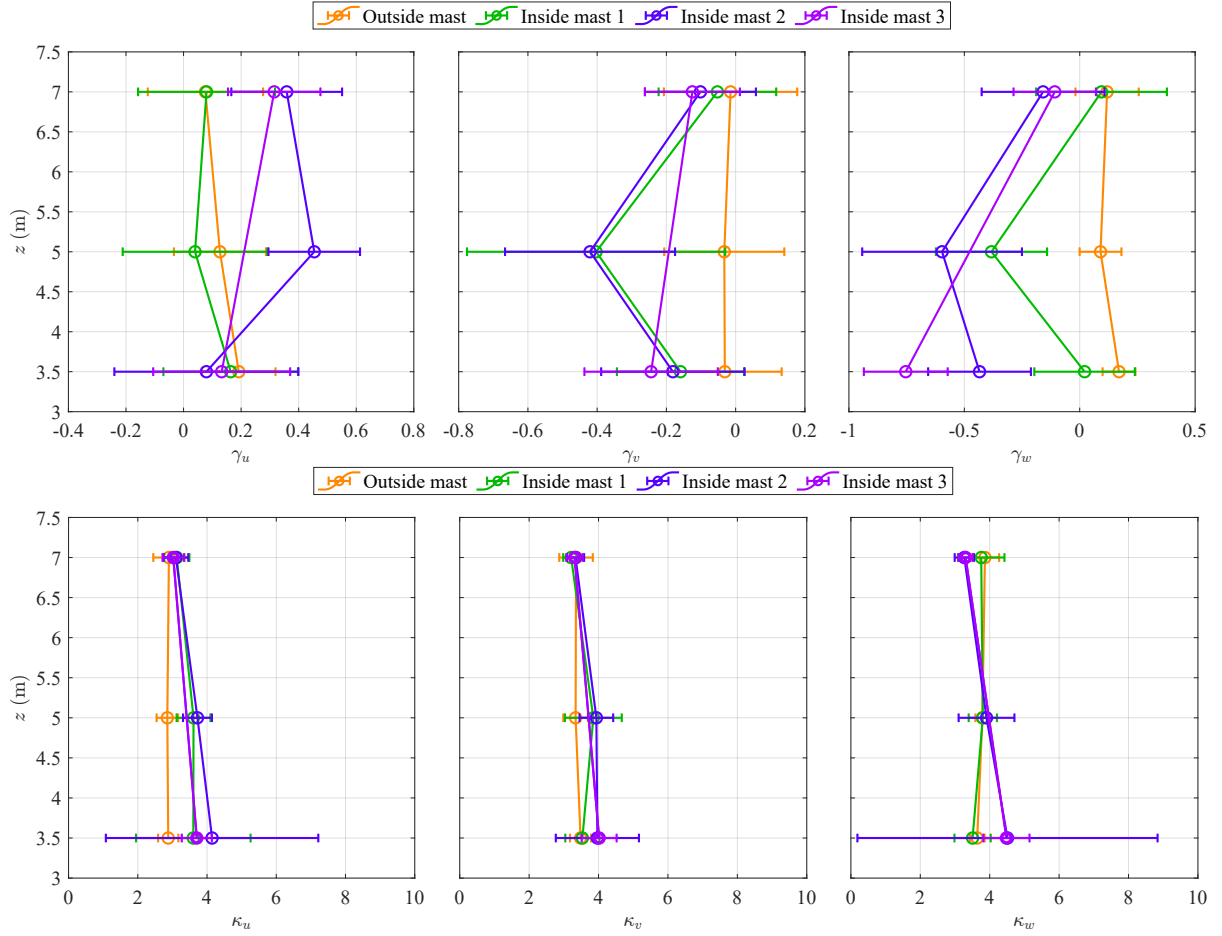


Figure 8. Skewness (top panels) and Kurtosis (bottom panels) of the wind velocity components u , v and w .

and a greater likelihood of intermittent, large fluctuations within the wakes [21]. The greater variability in the near-ground statistics of u and w components also show stronger variability near the ground, suggesting that ground effects, may reflect the combined effects of the ground and collector-induced flow separation and recirculation contribute significantly to uncertainty in the wake. As a result, the wake becomes less predictable and more prone to rapid changes in speed and direction.

4 Conclusions

The successive rows wake effects are often simplified in wind-resistant design. This study examined rows This study investigated the effects of parabolic trough collectors modification collector arrays on the mean flow and turbulence using the measured data from NSO. The wind data collected by sonic anemometers wind flow and integral turbulence characteristics using field measurements from the NSO. Sonic anemometer measurements at 3.5, 5 and 7 m were used to compare the undisturbed inflow with the wakes behind the examine the flow downstream of the first three collector rows .The motivation was to assess the shielding effect of upstream rows in mean wind and under near-perpendicular inflow conditions, with particular emphasis on the shielding effects of upstream collectors and the downstream evolution of turbulence.

Wind speed deficits of approximately 40–72% were observed The mean wind speed decreased

by approximately 21–80% relative to the inflow reference speed measured at 7 m, depending on height and downstream position. Most of this reduction occurred behind the first row, while the mean wind speeds behind the second and third rows were comparatively close. The first row also caused large wind direction deviation with comparatively small additional changes behind the subsequent rows. Wind direction deviations of approximately -98° and -85° were observed at 3.5 and 5 m. The wind direction partially recovered farther in the wake, respectively, with partial recovery further downstream. The incidence-angle deviation flow inclination angle also reached approximately 10° at 3.5 m, which indicates a slightly non-horizontal flow, indicating substantial vertical flow deflection within the wake.

At 3.5 and 5 m, the standard deviations of the streamwise (u) and lateral (v) velocity components decreased at 3.5 and 5 m but increased at 7 m relative to the inflow, with most of the change occurring behind the first row. At 7 m, both components increased compared with inflow. At each height, the standard deviations remained comparatively similar behind the successive undisturbed inflow. Most of these changes occurred downstream of the first row, with relatively little variation across subsequent rows. In contrast, σ_w increased at all the standard deviation of the vertical component (w) increased by 30–100% across the measured heights, with reported increases of approximately 30–100% and the largest increase further increases observed between the first two rows at 5 m. The available measurements also indicate a further increase in σ_w between the first and second wake locations. However, the 5 m measurement is missing at the third wake mast, so it is not possible to determine whether this downstream increase continues behind the third row. Skewness and kurtosis also differed from the inflow values, but no consistent downstream pattern was observed across the three velocity components and measurement heights. Skewness and kurtosis results also revealed further departures from Gaussian behaviour within the wakes, highlighting the anisotropic and intermittent nature of the velocity fluctuations.

This paper reveals the overall results demonstrate that the collector array generates a three-dimensional wake which focuses on the downstream development of the mean and turbulent flow. The changes of mean wind profile happened after in which the mean flow and turbulence evolve differently downstream. While the mean wind speed and horizontal velocity fluctuations change primarily behind the first row and it changes little farther downstream. At 3.5 and 5 m, horizontal turbulence is reduced, while vertical turbulence is amplified throughout the wake. As this paper uses the sample when the wind is perpendicular to solar array, future study should get insight to inflow wind with other yaw angles. The turbulence energy development in the downstream could also be analysed by power spectra.

Vertical fluctuations continue to develop further downstream. This behaviour suggests the onset of flow adjustment to the aerodynamic resistance of the collector array, although the available measurements cannot establish whether equilibrium is reached within the first three rows. Future investigations should consider a wider range of inflow wind directions and additional downstream positions. Spectral analysis would also help clarify how the observed changes in turbulence are distributed across frequencies.

Data availability

The wind and structural load data used in this study are openly available in the repository [22] associated with the publication by Egerer et al. [13].

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