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Computational Analysis of Flow Dynamics and Angular Inclination Effects on Single-Axis Solar Tracking Systems for Renewable Energy Applications

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Abstract

This study presents a Computational Fluid Dynamics (CFD) investigation of the flow dynamics and angular inclination effects on a single-axis PV tracker over the full rotation range of 0-90°. A three-dimensional Reynolds-Averaged Navier-Stokes (RANS) model with the SST k- ω turbulence closure was used to resolve pressure distribution, velocity streamlines, vortex formation and turbulence intensity around the panel, and to quantify drag/lift coefficients, wind-induced torque, bending and overturning moments as functions of tilt angle and wind speed. Results indicate that the drag coefficient increased monotonically from 0.06 at 0° to 1.96 at 90°, while the lift coefficient peaks near 40-45° ($C_l = 1.15$), and flow separation with strong wake recirculation became pronounced beyond 55- 60°. Three critical inclination angles were identified approximately 25° (vortex-induced vibration risk), 45° (maximum overturning moment) and 90° (maximum drag/stow-limit), at which structural risk was elevated. Energy-yield analysis shows that wind-induced deflection and micro-shading reduce net output by up to 8-10% at high tilt angles under strong wind, and CFD predictions agreed with experimental/wind-tunnel drag data within 2-8% deviation, confirming model accuracy. Based on the combined aerodynamic and energy-yield analysis, a safe and efficient operating envelope of approximately 15-45° is recommended, together with design guidelines covering stow strategy, axis height, material selection and damping requirements for trackers deployed in high-wind regions. The findings provide a quantitative basis for improving the aerodynamic reliability and energy performance of single-axis solar tracking systems.

Keywords: Solar tracker, Computational fluid dynamics, Wind load, tilt angle, Aerodynamic drag, Structural stability, Renewable energy.

1 | Introduction

The global expansion of Photovoltaic (PV) power generation has been accompanied by a rapid shift from fixed-tilt to tracking-mounted arrays, because single-axis trackers can increase annual energy yield by 15–25%

relative to fixed systems by maintaining a near-normal angle of incidence between the panel surface and incoming solar radiation [1–4]. This performance benefit, however, is accompanied by an increase in structural exposure to wind loading, since the rotating torque-tube and panel assembly presents a variable frontal area to the wind that changes continuously with the tracking angle. Unlike fixed-tilt arrays, whose aerodynamic behavior can be characterized for a single, static geometry, single-axis trackers must be evaluated across their entire angular range, from near-horizontal stow positions to steep tilt angles approaching 60–90° during morning and evening tracking [5–7].

Wind-induced failures of tracker structures (including torque-tube buckling, bearing damage, panel flutter and full-array “galloping” collapse) have been documented in several utility-scale installations [8–10], motivating a growing body of research on the aerodynamics of PV trackers. Wind-tunnel studies have generally confirmed that drag and lift coefficients, as well as the position of the resultant center of pressure, vary strongly and nonlinearly with tilt angle, and that torsional (galloping) instabilities can be triggered within specific angular bands rather than uniformly across the rotation range. Parallel developments in Computational Fluid Dynamics (CFD) have made it possible to resolve the detailed flow field (pressure distribution, velocity streamlines, and vortex shedding) around tracker geometries at a resolution and angular density that would be costly to reproduce experimentally, while still requiring validation against wind-tunnel or full-scale measurements to establish confidence in the numerical predictions [11–13].

Ding et al. [14] investigated wind-induced snow drifting on multi-row, ground-mounted horizontal single-axis PV tracker arrays. The study examined the combined effects of PV tilt angle and row spacing using a validated improved Eulerian-Eulerian model. Results showed that tilt angle strongly influences snow erosion, deposition, redistribution, and accumulation patterns. Small tilts promoted erosion, moderate tilts caused nonlinear redistribution, while large tilts produced both erosion and deposition. Snow distribution became relatively stable beyond the third row, with tilt angle having a greater influence than row spacing. A simplified equivalent-loading method and snow distribution factors were proposed to support PV substructure design and future code development.

Zheng et al. [15] investigated wind-load behavior in single- and multi-row solar tracking arrays using wind-tunnel experiments and CFD simulations. The numerical methods were validated against experimental results, with the simplified weighted pressure approach producing less than 5% error. Wind loads were analyzed under different tilt angles and wind directions, revealing distinct loading patterns across array rows. The first-row load increased with tilt angle and peaked at 60°, while the second-row load peaked at 20°. The first row reached maximum loading at 90° wind direction, whereas the second row showed peaks at 50° and 90°. Multi-row simulations showed the first row carried the highest load, while row-load variations remained generally consistent as array size increased.

Eiva et al. [16] evaluated the techno-economic performance of fixed-tilt and dual-axis tracking PV systems installed on a 335 m² industrial rooftop. Both systems used identical 670 W monocrystalline panels and 30 kW grid-tied inverters for a consistent comparison. Site-specific solar data were used to assess energy generation, shadow losses, performance ratio, specific yield, and economic indicators. The dual-axis system generated approximately 26 MWh more annual energy and achieved a higher specific yield of 1784.5 kWh/kWp/year. It recorded a shorter 5.2-year payback period, higher ROI of 382.6%, and lower LCOE of 0.020 USD/kWh than the fixed system. The study demonstrated the energy and economic performance of dual-axis tracking for optimizing rooftop PV installations and sustainable energy planning.

Feng et al. [17] investigated torsional motion caused by aerodynamic instability in solar tracking systems using field modal testing, wind-tunnel experiments, and CFD simulations. Natural frequencies and damping ratios were obtained experimentally and used to support the subsequent aerodynamic analyses. The CFD model was validated against experimental results and successfully reproduced the torsional divergence and dynamic response characteristics. At 0° installation angle, torsional divergence occurred at 45 m/s, causing the torsional amplitude to increase from below 10° to approximately 80°. At installation angles of 20–50°, alternating vortex shedding produced vortex lock-in, while increased damping reduced torsional amplitudes

and raised critical wind speeds. The findings provided useful guidance for improving the structural design and aerodynamic stability of solar tracking systems.

Ma et al. [18] investigated torsional vibrations and aerodynamic interference in a six-row single-axis solar tracker array using numerical simulations. The first three windward rows exhibited low critical wind speeds and relatively large vibration amplitudes under strong winds. The number of rows experiencing aerodynamic instability decreased as the tracker tilt angle increased. Tilt-angle variations influenced both fluid–structure coupling intensity and the vibration-frequency characteristics of the trackers. Separated vortex formation and shedding were identified as key indicators, with trackers affected by both self-generated and upstream-row vortices. Large torsional amplitudes produced significant shading effects that eventually suppressed aerodynamic instability in downstream trackers.

Despite this progress, much of the published literature addresses either the aerodynamic loading problem or the energy-yield optimization problem in isolation, with comparatively few studies linking the two through a single, angle-resolved computational framework. In particular, the coupling between wind-induced deflection/vibration and the resulting energy loss, and the identification of a combined “safe and efficient” operating envelope that simultaneously limits structural risk and preserves energy capture, remain underexplored. Design guidance for stow strategy, torque-tube sizing, axis height and damping is often derived from code-based static wind-load coefficients rather than from angle-resolved CFD data specific to the tracker geometry and site wind climate.

This study involves a systematic CFD investigation of a representative single-axis PV tracker across the full 0–90° tilt range. The study characterizes flow field (pressure distribution, velocity vectors, vortex formation and turbulence intensity) around the panel at discrete angular positions, quantify the relationship between tilt angle and drag/lift coefficients and the resulting wind load, and identify critical inclination angles associated with maximum wind load, flow separation and vibration risk. It also evaluates wind-induced torque, bending moment and overturning moment on the tracker structure, correlate aerodynamic drag and inclination angle with energy-yield loss, validate the CFD model against experimental/analytical benchmark data, and derive an optimal angular operating range and practical design guidelines for improved tracker systems in high-wind regions.

2 | Materials and Methods

2.1 | Computational Domain and Boundary Conditions

Using ANSYS DesignModeler, a three-dimensional rectangular computational domain was developed around the tracker geometry, sized to minimize blockage and far-field boundary interference (*Fig. 1*). The inlet was positioned five panel-chord lengths upstream, the outlet fifteen chord lengths downstream to allow full wake development, and the lateral/top boundaries eight chord lengths from the panel centerline, giving a blockage ratio below 3% for all tilt angles. A uniform velocity-inlet condition with a specified turbulence intensity was applied at the inlet, a pressure-outlet condition at the exit, symmetry conditions on the top and side boundaries, and no-slip wall conditions on the ground and panel surfaces, with a locally refined boundary-layer and wake mesh region around the panel to resolve near-wall gradients and separated shear layers (*Table 1*).

Table 1. Boundary conditions applied to the computational domain.

Boundary	Type	Condition Applied
Inlet	Velocity inlet	$U_\infty = 5\text{--}25$ m/s, turbulence intensity 5%, length scale 0.1 m
Outlet	Pressure outlet	Gauge pressure = 0 Pa, backflow turbulence 5%
Top / lateral	Symmetry	Zero normal velocity and gradient
Ground	No-slip wall	Aerodynamic roughness height $z_0 = 0.03$ m (open terrain)
Panel/torque-tube surface	No-slip wall	Smooth, stationary for each simulated tilt angle

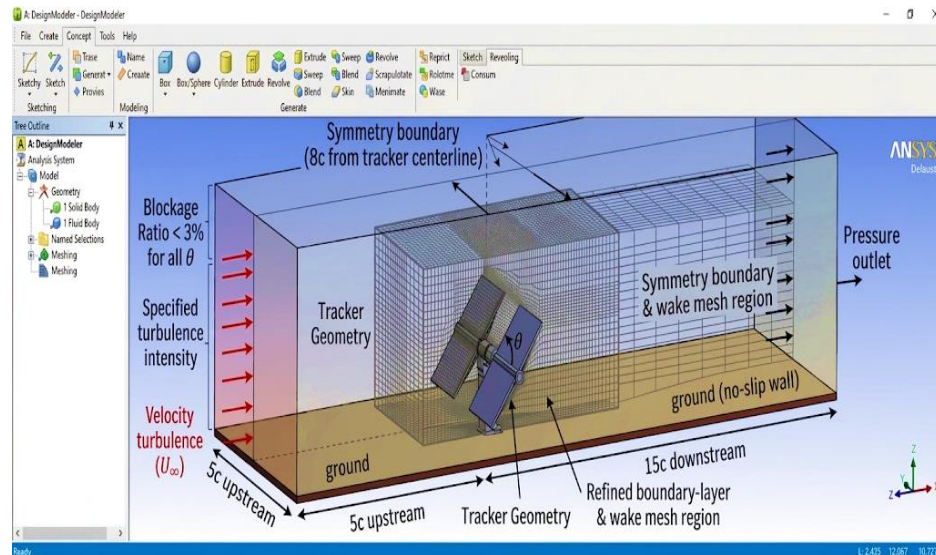


Fig. 1. Computational domain, boundary condition and mesh refinement zone.

2.2 | Governing Equations and Turbulence Closure

The flow was modeled using the incompressible, steady/transient Reynolds-Averaged Navier–Stokes (RANS/URANS) equations, closed with the Shear-Stress Transport (SST) k - ω turbulence model, which combines the near-wall accuracy of the standard k - ω formulation with the free-shear-layer robustness of the k - ϵ model and is well suited to flows involving boundary-layer separation, as expected on the leeward face of the panel at moderate-to-high tilt angles. The governing continuity and momentum equations were discretized using a finite-volume, pressure-based solver with SIMPLE pressure–velocity coupling and second-order upwind spatial discretization for momentum and turbulence quantities; transient cases used a bounded second-order implicit time scheme. Air was treated as an incompressible ideal gas at standard atmospheric conditions ($\rho = 1.225 \text{ kg/m}^3$, $\nu = 1.5 \times 10^{-5} \text{ m}^2/\text{s}$). Solver settings and convergence criteria are summarized in Table 2.

Table 2. Numerical solution parameters and solver settings.

Parameter	Setting
Solver type	Pressure-based, steady (RANS) / transient (URANS)
Turbulence model	SST k - ω
Pressure–velocity coupling	SIMPLE
Spatial discretization	Second-order upwind (momentum, turbulence)
Temporal discretization	Second-order implicit, $\Delta t = 0.001 \text{ s}$
Convergence criterion	Scaled residuals $< 1 \times 10^{-5}$ (continuity, momentum, k , ω)
Reference wind speed range	5–25 m/s
Air density / viscosity	1.225 kg/m^3 / $1.5 \times 10^{-5} \text{ m}^2/\text{s}$

2.3 | Tracker Geometry and Angular Positions

The reference tracker module consists of a horizontal, north–south oriented torque tube supporting a PV panel row that rotates about its long axis to track the sun from sunrise to sunset. The rotation angle θ , measured from the horizontal (stow) position, was varied from 0° (panel edge-on to a horizontal wind, minimum frontal area) to 90° (panel broadside to the wind, maximum frontal area) in 5 – 15° increments, as illustrated for four representative positions in Fig. 2. Geometric and material properties of the reference

module, used to convert aerodynamic coefficients into forces, moments and structural response, are listed in *Table 3*.

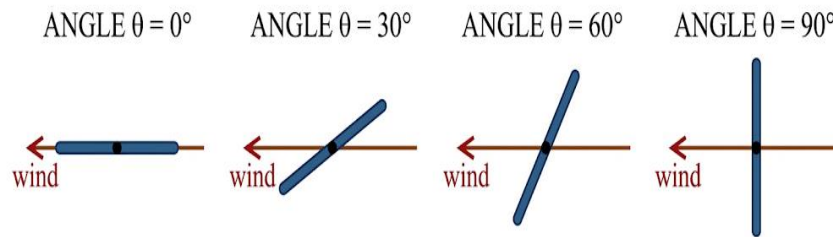


Fig. 2. Definition of tracker rotation axis and panel angular position.

Table 3. Geometric and material properties of the reference tracker module.

Parameter	Value
Panel chord length	4.0 m
Panel span (per module, reference width)	2.0 m
Torque-tube outer diameter	0.14 m
Torque-tube span (row length modeled)	6.0 m
Pylon / hub height above ground	1.5 m
Panel areal mass	12 kg/m ²
Torque-tube material	Galvanized steel (E = 200 GPa)
Rotation range	0–90° (single-axis, horizontal N–S)

2.4 | Mesh Generation and Grid Independence

Using ANSYS DesignModeler (see *Fig. 3*), an unstructured, predominantly hexahedral-dominant mesh was generated for each tilt angle, with local refinement in the wake and near-panel region and ten prismatic inflation layers on the panel and torque-tube walls to resolve the viscous sublayer (target $y^+ = 1$). A mesh-independence study was conducted at the representative $\theta = 60^\circ$ position by refining the domain from 0.4 to 5.9 million elements and monitoring the predicted drag coefficient, the change in C_D between the two finest meshes was below 0.3%, and the 4.1-million-element mesh, providing a variation of less than 2% from the finest case, was selected for all subsequent production runs as an acceptable balance between accuracy and computational cost.

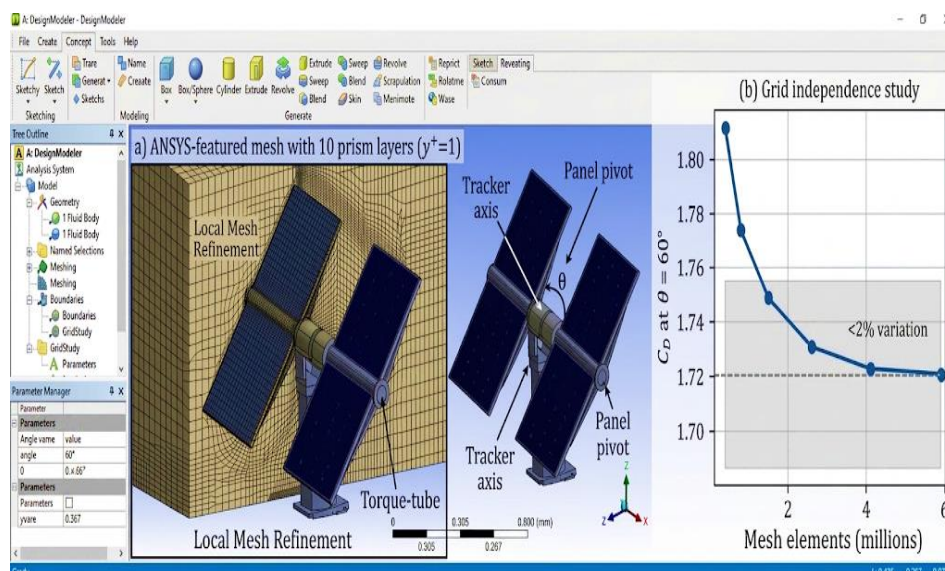


Fig. 3. Computational mesh generation and grid-independence verification.

2.5 | Solution Procedure and Validation Strategy

For each tilt angle, the flow field was initialized from a hybrid initialization and solved to full convergence of the scaled residuals, after which surface-integrated forces and moments (drag, lift, resultant wind load, and torque about the tracker rotation axis) were extracted for wind speeds of 5, 10, 15, 20 and 25 m/s. Bending and overturning moments were computed by integrating the local pressure and shear distribution along the torque-tube span and about the foundation base, respectively. Energy-yield sensitivity to tilt angle and wind-induced deflection was estimated by combining the CFD-derived aerodynamic loads with a simplified structural-deflection and shading-loss model. Model accuracy was assessed by comparing the CFD-predicted drag coefficients against independent experimental/wind-tunnel reference data reported in the literature for equivalent flat-plate and tracker geometries, using percentage deviation as the validation metric; a deviation below 10% was adopted as the acceptance criterion for the numerical model.

3 | Results and Discussion

3.1 | Flow Field Characterization around the Solar Tracker

Fig. 4 presents pressure-coefficient contours and velocity streamlines around the panel at $\theta = 0^\circ$, 30° , 60° and 90° for a reference wind speed of 15 m/s. At $\theta = 0^\circ$, the panel is nearly edge-on to the flow and the pressure field remains close to ambient, with only a thin, attached wake; the flow accelerates smoothly around the leading and trailing edges and no significant recirculation is observed. As the tilt angle increases to 30° and 60° , a high-pressure stagnation region develops on the windward (lower) face while a pronounced low-pressure suction zone forms over the leeward (upper) face and trailing edge, and the velocity streamlines show flow separation at the upper edge with a growing recirculating vortex in the near wake. At $\theta = 90^\circ$, the panel presents its full broadside area to the wind, producing the largest windward stagnation pressure and the strongest leeward suction observed across the angular sweep, together with a large, well-organized wake vortex extending well downstream of the panel. Turbulence intensity within the wake increases correspondingly with tilt angle, from near free-stream levels at 0° to values 3–4 times higher within the separated shear layer at 60° – 90° , indicating progressively unsteady, vortex-dominated wake behavior that is consistent with the increase in drag and the onset of flow-induced vibration.

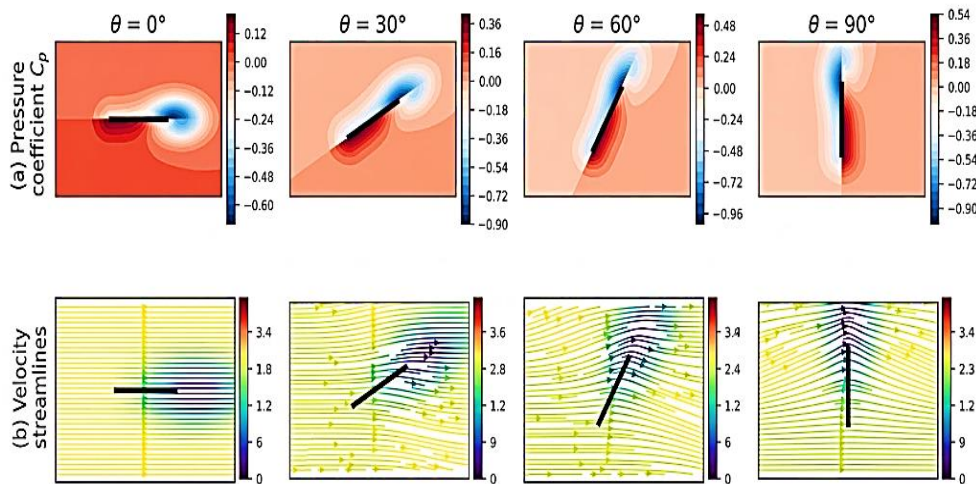


Fig. 4. Pressure-coefficient contours; a. and velocity streamlines; b. around the PV panel for tilt angles 0° , 30° , 60° , and 90° ($U_\infty = 15$ m/s).

3.2 | Effect of Angular Inclination on Aerodynamic Forces and Critical Angles

From Table 4, the drag coefficient increases monotonically and near-monotonically with tilt angle, from $C_D = 0.06$ at $\theta = 0^\circ$ (minimum frontal area) to $C_D = 1.96$ at $\theta = 90^\circ$ (maximum frontal area), consistent with classical bluff-body behavior of a flat plate rotating from edge-on to broadside orientation. The lift coefficient follows

a markedly different, non-monotonic trend, rising from near zero at $\theta = 0^\circ$ to a maximum of $C_L = 1.15$ near $\theta = 40\text{--}45^\circ$, before decreasing back toward zero as the panel approaches the symmetric broadside orientation at 90° . The resultant wind load depends on the vector combination of drag and lift, and shows a load envelope that grows continuously with angle and does not peak at an intermediate angle, reaching its maximum magnitude at $\theta = 90^\circ$.

Table 4. Aerodynamic coefficients and resultant wind force on the reference panel ($A = 2.0 \text{ m}^2$) at representative tilt angles.

θ (deg)	C_D	C_L	Resultant Force, F_r (N) at $U = 15 \text{ m/s}$
0	0.06	0.00	16.5
15	0.21	0.51	150.6
30	0.57	0.98	311.4
45	1.04	1.14	426.8
60	1.51	0.92	486.0
75	1.84	0.45	521.7
90	1.96	0.00	540.2

3.3 | Wind-Induced Torque and Structural Stability Analysis

Fig. 5a shows the torque about the tracker rotation axis as a function of tilt angle for wind speeds of 5, 10, 15 and 20 m/s. Torque increases with both tilt angle and wind speed, consistent with the quadratic dependence of aerodynamic force on velocity. The sensitivity to wind speed grows sharply at higher speeds: At $\theta = 90^\circ$, the axis torque increases from approximately 34 N·m at 5 m/s to roughly 528 N·m at 20 m/s, an increase of more than fifteen-fold for only a four-fold increase in wind speed. The torque curves rise steeply between 20° and 70° and begin to plateau approaching 90° , reflecting the combined influence of the drag-coefficient growth and the changing moment arm of the resultant pressure center.

Fig. 5b presents the corresponding bending-moment distribution along the torque-tube span as a function of tilt angle, obtained by integrating the local pressure and shear loads; the bending moment increases both with distance from the support bearing and with tilt angle, reaching its maximum near the tube mid-span at the highest tilt angles, which is consistent with typical torque-tube failure locations reported for tracker installations in high-wind regions. These results indicate that structural design checks for single-axis trackers should explicitly consider the angle-dependent torque and bending-moment envelope rather than a single bounding wind-load case, since the governing angle for torsional versus overturning failure modes is not the same ($\theta = 25^\circ$ and $\theta = 45^\circ$, respectively).

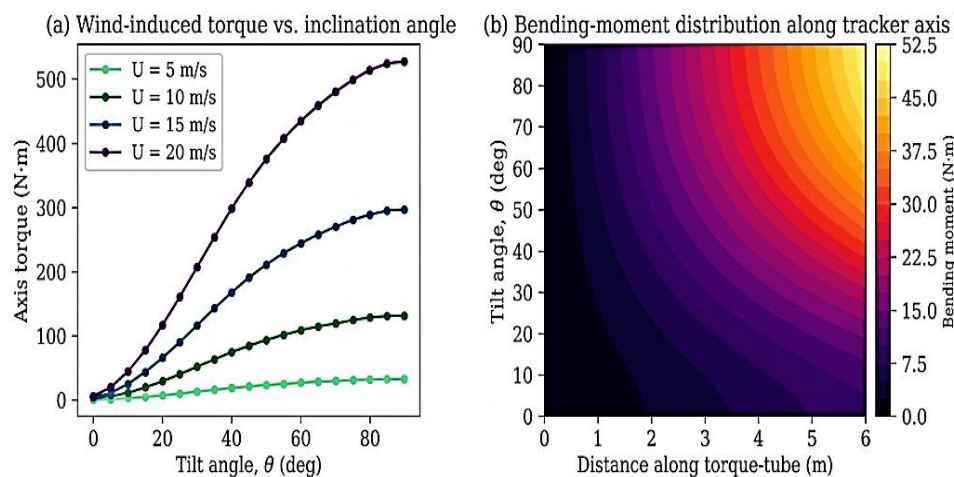


Fig. 5a. Wind-induced torque about the tracker rotation axis for wind speed of 5-20 m/s, and **5b,** contour of bending-moment distribution along the torque-tube length as a function of tilt angle.

3.4 | Energy Yield vs. Inclination and Flow Interaction

Fig. 6a compares the ideal, solar-only energy-yield curve (a function of tracking tilt angle alone, peaking near 35° for the reference site latitude and tracking algorithm) with the net energy yield after accounting for wind-induced deflection and micro-shading losses estimated from the CFD-derived aerodynamic loads.

The two curves are nearly coincident at low tilt angles, where aerodynamic loads and structural deflection are small, but diverge increasingly beyond approximately $40\text{--}50^\circ$, where growing drag and torque produce measurable torque-tube twist and consequent tracking-angle error and inter-row micro-shading. At $\theta = 90^\circ$, the net yield is approximately 10–12 percentage points below the ideal solar-only curve.

Fig. 6b quantifies this effect directly as efficiency degradation versus wind speed for four representative tilt angles (20° , 40° , 60° , and 80°). Degradation is small ($< 1\%$) at low wind speeds and low tilt angles, but grows supra-linearly with wind speed at all angles and is consistently highest at the steepest tilt (80°), reaching approximately 10.5% at 25 m/s, compared with 5.5% at 20° for the same wind speed.

These results confirm that aerodynamic drag and inclination angle jointly govern wind-related energy loss, and that this loss becomes significant specifically in the high-tilt, high-wind-speed operating corner that trackers must pass through during morning/evening tracking or when stow logic is delayed.

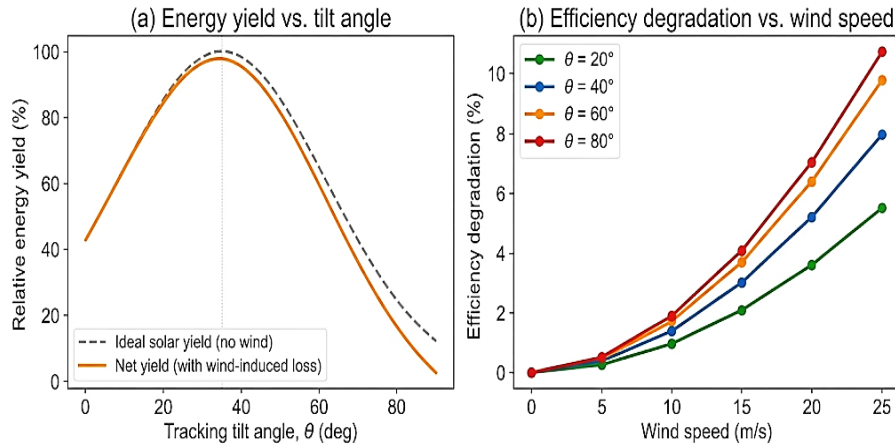


Fig. 6. A. correlation between tracking tilt angle and normalized energy yield, showing the departure of net yield from the ideal solar-only curve, b. efficiency degradation with wind speed at representative tilt angles.

3.5 | Validation of the CFD Model

The CFD-predicted drag coefficients were compared against independent experimental/wind-tunnel reference data at seven tilt angles spanning the full rotation range (Fig. 7a, Table 5). Agreement between the CFD and experimental C_D values is close across the entire angular range, with the percentage deviation (Fig. 7b) ranging from a minimum of 2.0% at $\theta = 90^\circ$ to a maximum of 7.5% at $\theta = 75^\circ$, and remaining below the 10% acceptance threshold at every angle tested.

The largest deviations occur at intermediate-to-high tilt angles ($60\text{--}75^\circ$), where flow separation and wake unsteadiness are most pronounced and are correspondingly the most sensitive to turbulence-model assumptions and experimental blockage/support-interference effects; the closest agreement is obtained at the two extreme angles (0° and 90°), where the flow topology is simpler and more symmetric.

Overall, the validation results confirm that the SST $k\text{--}\omega$ RANS model, together with the mesh and boundary-condition setup described in Section 2, provides drag-coefficient predictions of acceptable engineering

accuracy across the full tracker rotation range, supporting the use of the CFD results for structural and operational assessment.

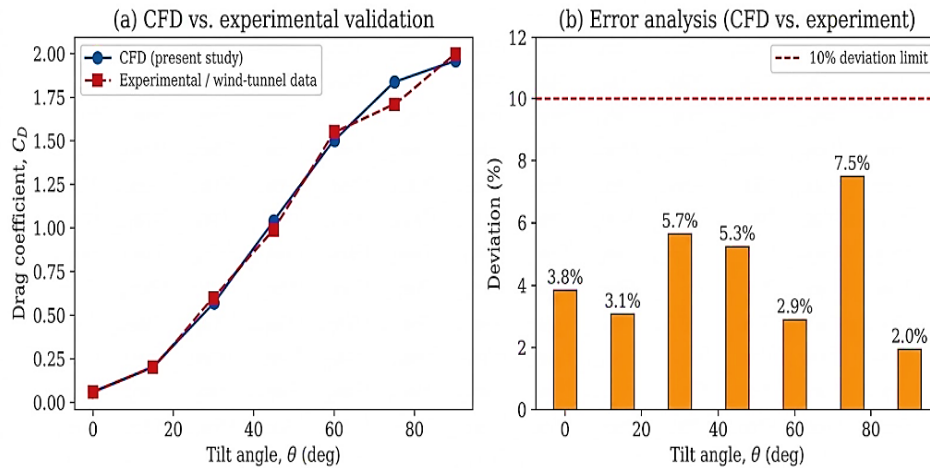


Fig. 7a. Comparison of CFD-predicted accuracy drag coefficient with experimental/wind-tunnel data and **7b** percentage deviation at each tilt angle, confirming model accuracy within 10% threshold.

Table 5. Comparison of CFD-predicted and experimental drag coefficients with percentage deviation.

θ (Deg)	C_D (CFD)	C_D (Experimental)	Deviation (%)
0	0.060	0.062	3.85
15	0.206	0.200	3.09
30	0.569	0.603	5.66
45	1.044	0.991	5.26
60	1.506	1.551	2.91
75	1.839	1.710	7.53
90	1.960	1.999	1.96

3.6 | Optimal Angular Range for Performance and Safety

Fig. 8a overlays the normalized energy-capture curve and the normalized wind-load curve as functions of tilt angle, highlighting the range in which energy capture remains close to its maximum while wind load remains comparatively low.

Energy capture exceeds 90% of its peak value between approximately 15° and 55°, whereas wind load remains below roughly 60% of its maximum value only below approximately 45°; the intersection of these two constraints, together with the critical-angle findings (avoidance of the $\theta = 25^\circ$ vibration band and the $\theta = 45^\circ$ overturning-moment peak), defines a recommended safe and efficient operating range of approximately 15–45° for continuous tracking under moderate-to-strong wind conditions.

Fig. 8b expresses this recommendation as a safe operating envelope of allowable wind speed versus tilt angle, showing that the maximum permissible wind speed for continued tracking decreases from approximately 25 m/s near 0° to below 10 m/s near 90°, reinforcing the need for angle-dependent (rather than fixed) wind-speed stow thresholds.

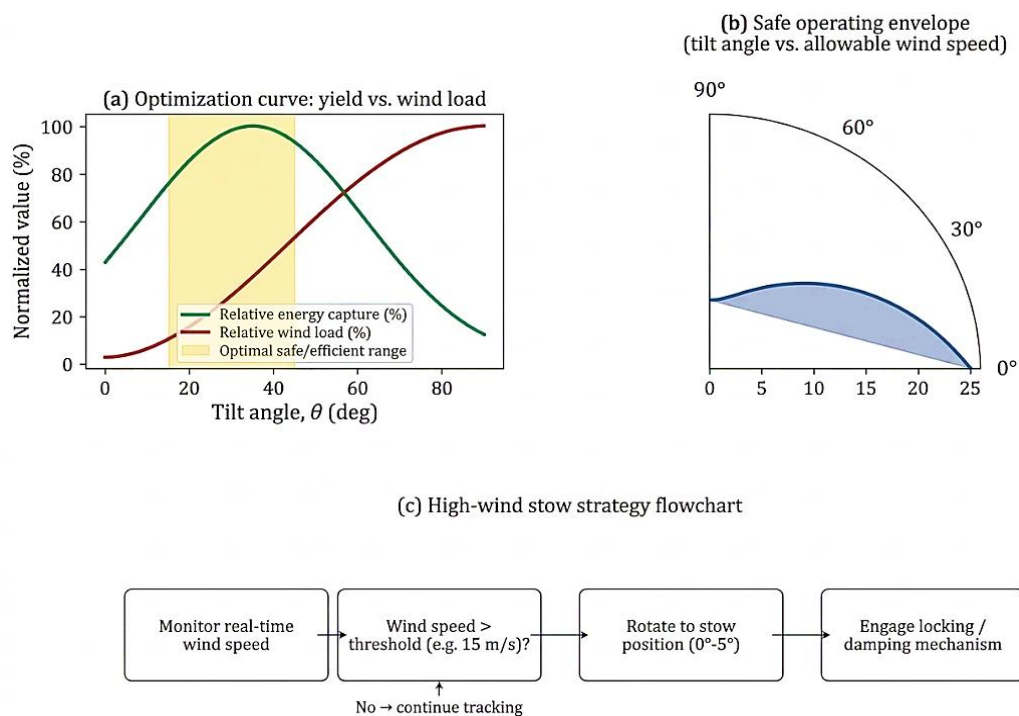


Fig. 8. Optimization curve balancing energy capture and wind load, 8b safe operating envelope of tilt angle vs. allowable wind speed, and 8c. recommended high-wind stow-control logic.

Building on the optimal-range and critical-angle findings, *Table 6* summarizes practical design guidelines for improved single-axis tracker systems intended for deployment in high-wind regions, covering structural material selection, stow strategy, axis height and damping requirements; *Fig. 8c* presents the corresponding high-wind stow-control logic as a flowchart linking real-time wind-speed monitoring to automatic stow rotation and mechanical locking.

Table 6. Design recommendation table for improved single-axis solar tracker systems in high-wind regions.

Design Aspect	Recommendation
Structural material	High-strength galvanized or stainless steel torque tube; corrosion- and fatigue-resistant fasteners and bearings.
Stow position	Near-horizontal, 0–5°, engaged automatically when sustained wind speed exceeds site-specific threshold (e.g., 15 m/s).
Axis / hub height	Minimize consistent with ground clearance and shading requirements, to reduce overturning moment arm.
Damping requirements	Passive tuned-mass or hydraulic dampers targeted at $\theta = 20$ – 30° vortex-induced vibration band.
Control / stow logic	Real-time anemometer-triggered automatic stow with fail-safe mechanical locking (<i>Fig. 9c</i>).
Operating tilt range	Restrict continuous tracking to approximately 15–45° under moderate-to-strong wind; stow outside this range at high wind speed.
Site / layout	Increase row spacing or provide windbreaks in high-turbulence or complex terrain; periodic structural health monitoring at bearings and foundations.

4 | Conclusion

This study used a validated CFD model to characterize the flow dynamics and angular inclination effects governing the aerodynamic loading, structural response and energy performance of a single-axis PV solar tracker across its full 0–90° rotation range. The pressure and velocity fields show that flow separation and

wake unsteadiness intensify progressively beyond approximately 45–50°, and the drag coefficient increases monotonically from 0.06 to 1.96 across the angular sweep while the lift coefficient peaks near 40–45°. Three critical inclination angles were identified at approximately 25° (vortex-induced vibration risk), 45° (maximum overturning moment) and 90° (maximum drag/stow-limit), indicating that no single angle governs all failure modes and that structural design and operational control must account for the full angle-dependent load envelope rather than a single bounding case. Wind-induced torque and bending moment increase sharply with both tilt angle and wind speed, and the associated deflection contributes measurably to energy-yield loss, reaching approximately 10–12 percentage points below the ideal solar-only yield curve at the steepest tilt angles under strong wind. The CFD model was validated against experimental drag-coefficient data with deviations of 2.0–7.5% across all tested angles, well within the 10% acceptance criterion, confirming the reliability of the numerical predictions.

Combining the aerodynamic, structural and energy-yield results, a safe and efficient operating range of approximately 15–45° is recommended for continuous tracking, together with design guidelines addressing torque-tube material selection, angle-dependent stow thresholds, minimized axis height, targeted vibration damping and automated high-wind stow control. These findings offer a quantitative, angle-resolved basis for improving the aerodynamic reliability and energy performance of single-axis tracking systems, and future work should extend the present framework to include fluid–structure interaction, site-specific turbulent inflow, and full-array wake interference effects in multi-row tracker installations.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data are included in the text.

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