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Accuracy-cost trade-offs in LES: assessing the impact of reduced spatial and temporal resolution

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SUMMARY

Although the application of computational fluid dynamics (CFD) for wind load assessment has been successfully demonstrated, its adoption in practical engineering design remains limited due to the lack of standardized procedures. The upcoming ASCE 7 pre-standard for computational wind engineering (CWE) aims to address this gap by providing a CFD modeling framework for wind load applications. For such applications, scale-resolving simulations like large-eddy simulation (LES) are required, but their computational cost is a major constraint. This study examines how mesh resolution and solver time-step refinement affect LES predictions for single-axis solar tracker (SAT) wind loads and the associated computational costs. The high-fidelity LES case achieved percentage-root-mean-square errors (PRMSE) below 10% across all pressure taps, confirming its reliability for engineering design. The full paper further assesses reduced-fidelity LES to quantify cost-accuracy trade-offs for preliminary design stages.

Keywords: *CFD, LES, Wind tunnel, CWE standards, Single-axis solar trackers, Wind loading*

1. INTRODUCTION

Several studies have demonstrated the capability of CFD to simulate wind flow around solar arrays and predict aerodynamic loads. Earlier studies relied on steady-state simulations to characterize mean aerodynamic behavior, while more recent studies employ transient methods such as large-eddy (LES) and detached-eddy simulation (DES) to capture peak loads. These studies typically validate their CFD approach against experimental or full-scale data. Despite the significant research progress, most design codes still prohibit the use of CFD for wind load evaluation, and industry adoption remains limited to applications such as pedestrian-level wind and building performance. A recent workshop on advances in computational wind engineering (Scott et al., 2023) highlighted the need for standardized procedures and guidelines to support the broader use of CFD in engineering design.

An upcoming ASCE 7 pre-standard for computational wind engineering (CWE) simulations aims to establish clear guidelines for appropriate CFD modeling to support engineering design (Scott et al., 2023). Scale-resolving simulations such as LES are required for accurate wind load prediction, but their high computational cost remains a major barrier to routine industry use. Understanding the trade-off between computational expense and predictive accuracy is therefore essential. This study examines how mesh resolution and solver time-step refinements influence the accuracy of LES predictions for solar array wind loads. The full analysis will assess the viability of reduced-fidelity LES for preliminary design and quantify the associated cost-accuracy trade-offs. The findings aim to inform the practical use of CFD for solar array design within the emerging CWE framework.

2. METHODOLOGY

This study extends from a broad benchmark validation campaign covering 35 SAT array configurations tested in BLWT. Figure 1 illustrates the aerodynamic model and relevant geometric parameters. Although 15 configurations were replicated in LES, this accuracy-focused parametric study centers on a single case with $\alpha = 30°$, $S/B = 2.8$, $H/B = 0.75$, and $\theta = 0°$. The following section briefly describes the target BLWT experiment, and LES setup used in the analysis.

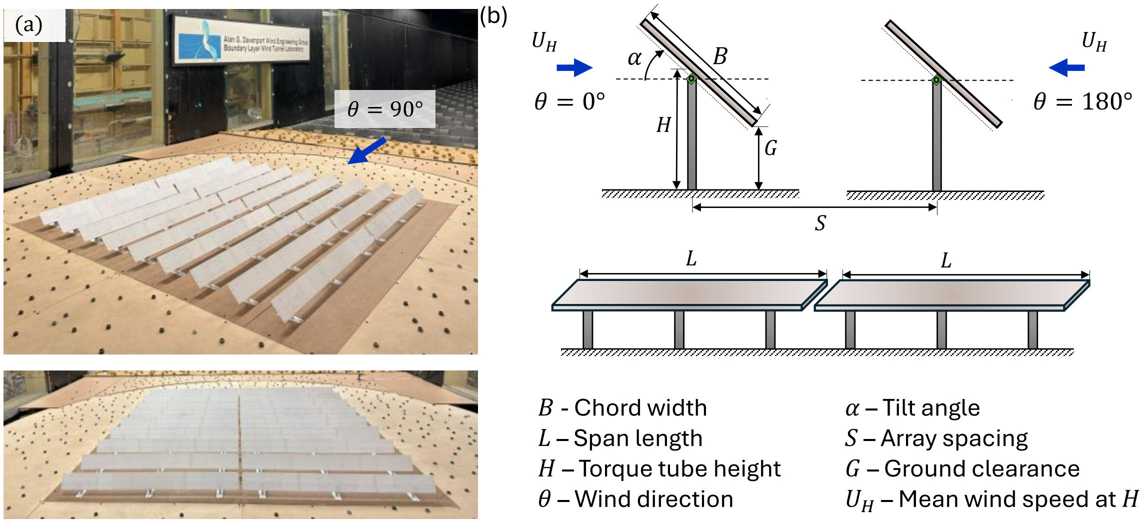


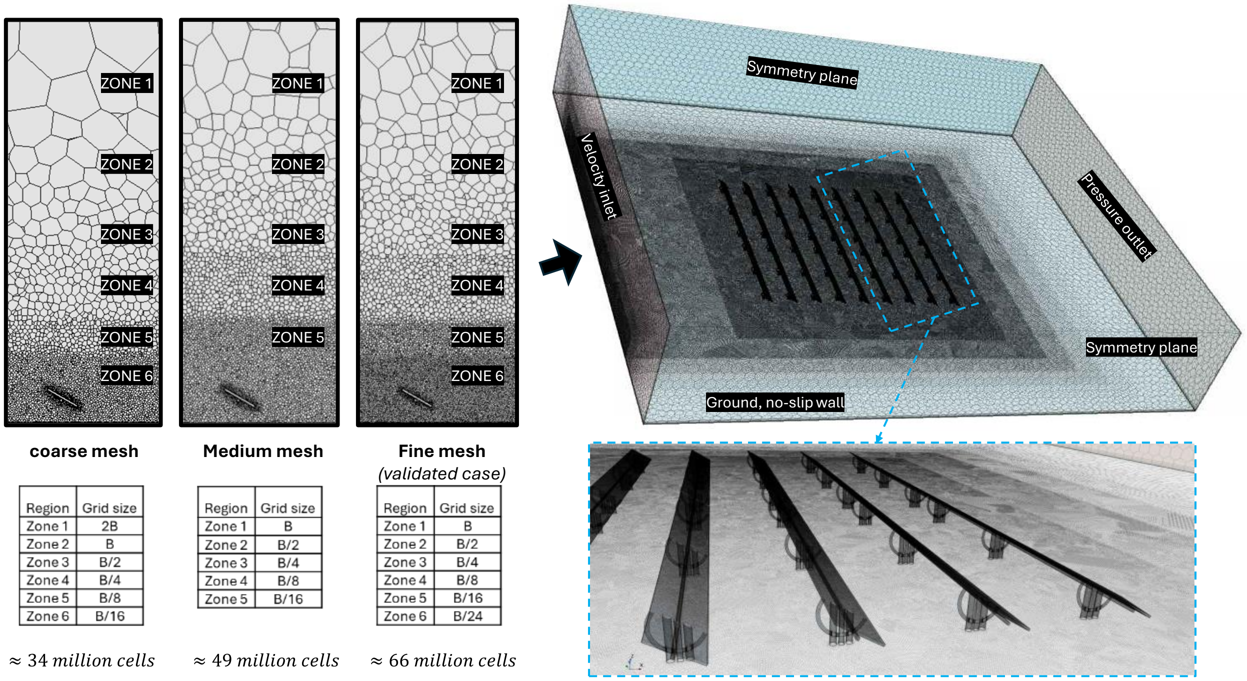
Figure 1: (a) SAT array in BLWT and (b) relevant parameters

2.1. Benchmark wind tunnel experiment

The benchmark BLWT database includes 35 array configurations obtained by varying tilt angle (0°–60°), height (1.5–1.71 m), ground coverage ratio (0.35–0.41), and terrain roughness (E2, $z_O = 0.03$; E3, $z_O = 0.05$). The aerodynamic model was designed according to ASCE, (2021) guideline, with particular attention given to minimizing interference from instrumentation and auxiliary supports. The tests were performed at a 1:30 geometric scale, with wind direction varied from 0° to 180° in 10° increments. Additional details on the BLWT test setup, data quality, and results are provided in Eshete et al., (2026).

2.2. LES setup

The LES replicated the WT model, including auxiliary supports, pressure tubing bundles beneath the panels, and the tap layout. Figure 2 shows the computational domain and grid discretization for the 30° tilt array at 0° wind direction. Three grid sizes: coarse, medium, and fine, with approximately 34, 49, and 66 million cells respectively, and three solver time-steps of 0.0003, 0.0006, and 0.001 seconds are evaluated. The most refined simulation (fine mesh, $\Delta t = 0.0003$) is validated against the target BLWT data within a 10% error margin. Its grid and time-step were determined using Equation (7) in Eshete et al., (2024) to resolve turbulence up to a reduced frequency of 1 ($f_c = n_c B/U_H \geq 1$), as required by ASCE, (2021). For components and cladding, higher resolution is recommended with f_c greater than 2 (Geleta and Bitsuamlak, 2022). The validated case required approximately 1,440 hours (60 days) of continuous computation on 225 CPUs. The computational cost of the lower-fidelity cases will be discussed in the full paper.



Region	Grid size
Zone 1	2B
Zone 2	B
Zone 3	B/2
Zone 4	B/4
Zone 5	B/8
Zone 6	B/16

Region	Grid size
Zone 1	B
Zone 2	B/2
Zone 3	B/4
Zone 4	B/8
Zone 5	B/16

Region	Grid size
Zone 1	B
Zone 2	B/2
Zone 3	B/4
Zone 4	B/8
Zone 5	B/16
Zone 6	B/24

Figure 2: Computational domain and grid discretization

3. RESULTS AND DISCUSSION

The validation follows a two-step simulation process: approach-flow validation using an empty domain and aerodynamic validation using the main domain simulation. The empty-domain setup replicates the geometry and solver settings of the main simulation, excluding the structure and the local mesh refinement in Zone 6.

Figure 3 presents the approach flow and aerodynamic validation results for the high-fidelity LES case. The LES closely matches the BLWT mean velocity (U), longitudinal turbulence intensity (I_U), and integral length scale (${}^{X}L_U$) profiles within the lower 5H region of the boundary layer. The spectral energy distribution is well resolved up to the cutoff frequency $f_c \leq 1$, with minor differences in energy amplitude across frequencies, including within the active reduced-frequency range (0.1–2) that governs the aerodynamics (Geleta and Bitsuamlak, 2022; Morrison and Kopp, 2018). Approximately 95% of the total turbulent kinetic energy (TKE) is resolved, surpassing the 80% criteria (Pope, 2000).

Figure 3b shows scatter plots of the mean ($\bar{C}_P$), standard deviation (σ_{C_P}), and peak ($\hat{C}_P$) pressure coefficients across all pressure taps for the validated case. The percentage root-mean-square error (PRMSE) is defined as the RMSE normalized by the range of each C_P statistics in the BLWT database. Case 5 demonstrates robust agreement with BLWT measurements, with PRMSE under 10% across all 912 pressure taps. The full paper will examine the error margins and computational cost of the lower fidelity LES cases. It will also review the general requirements, performance objectives, and acceptance criteria in the context of solar array wind loads.

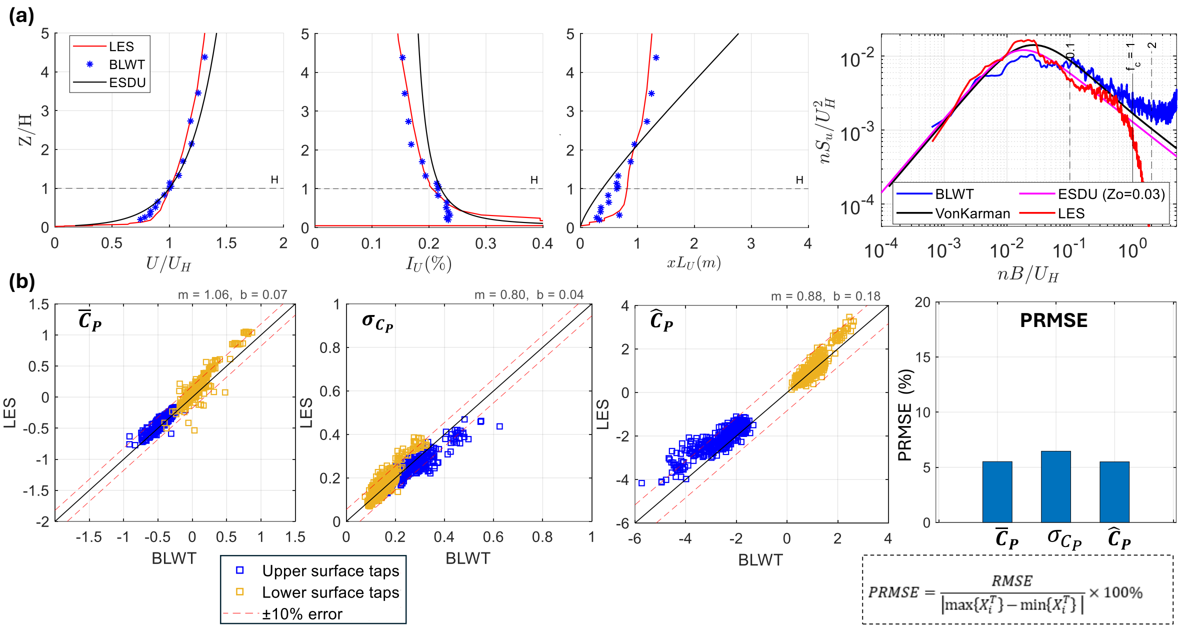


Figure 3: (a) approach flow and (b) aerodynamic validation

4. CONCLUSIONS

A rigorous validation campaign was performed using a BLWT database of 35 SAT array configurations. This study examines three mesh resolutions and three solver time-steps to quantify the trade-off between CFD accuracy and computational cost. The high-fidelity LES showed strong agreement with the BLWT data, with PRMSE below 10% across all pressure taps. The study confirms that LES can deliver reliable wind load data for solar tracker array design. The full paper will assess the suitability of low-fidelity LES for early design stages and the associated cost-accuracy trade-offs.

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