CFD Analysis of Solar Awning

Cooperative Research and Development Final Report

CRADA Number: CRD-22-22483

NREL Technical Contacts: Michael Kuhn and Eliot Quon

NREL is a national laboratory of the U.S. Department of Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-91330
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Cooperative Research and Development Final Report

Report Date: September 13, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Alliance for Sustainable Energy, LLC and Portable Solar Inc

CRADA Number: CRD-22-22483

CRADA Title: CFD Analysis of Solar Awning

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

Michael Kuhn | michael.kuhn@nrel.gov

Eliot Quon | eliot.quon@nrel.gov

Name and Email Address of POC at Company:

Dennis Nickerson | dennis@portablesolar.io

Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$50,000.00
TOTALS	$50,000.00

Executive Summary of CRADA Work:

Using computational fluid dynamics (CFD), we will simulate the wind loading on a solar awning that is attached to the wall of a manufactured home while being towed behind a semi-truck.

CRADA benefit to DOE, Participant, and US Taxpayer:

Uses the laboratory's core competencies

Summary of Research Results:

Original Purpose: To simulate air flows around a solar PV awning attached to the wall of a manufactured home while the home is being towed down the highway at different speeds.

Revised Purpose: To simulate air flows around a solar PV awning attached to the wall of a manufactured home in different environments prior to and after deployment.

Technical Summary:

The initial phase of the project investigated loading on solar awnings while stowed in transit. These panels were modeled as surfaces flush to the wall of a portable home. In unsteady RANS simulations, the most significant forces these model awnings experienced was 300 lb-f and changing the wind direction produced unsteady loads of up to 100 lb-f on the leeward side. These simulations clarified that the wind loading from transit would not exceed the original requirements from design standards. The second phase of the project investigated the wind loading on deployed solar awnings exposed to weather. After performing simulations with a variety of wind speeds and directions, the most significant loading occurred as a moment about the awning mount, pushing the awning upward. The biggest driver of this moment, which almost reached 4000 lb-ft, was an upward force of up to 1500 lb-f. This loading occurs when the wind flows opposed to the side of the structure and downward. When it reaches the awning, part of the flow diverts above it, accelerating over the structure and lowering the pressure above the awning, whereas part of the flow diverts below it to form a slow recirculation region, maintaining a higher pressure below the awning. All work in this project used tools within the open-source, DOE-funded ExaWind software suite[1].

Task 1: Problem Definition

Subtask A: Work with participant to identify test conditions of interest: truck speed, wind speed, wind direction (headwind, tailwind, or crosswind); other considerations may include the mean wind profile and/or ambient turbulence.

- In discussions with the participant, we decided that a truck speed of 65 mph and an ambient wind speed of 30 mph would be sufficient. We would consider the angles of 0, 45, and 90 degrees from the incoming relative airspeed due to the motion of the truck. No additional complexities were added to the inflow profile, but the intended use of turbulence modeling was emphasized to properly captured wake dynamics.

  Subtask B: Work with participant to identify home/PV configurations of interest, e.g. the angle of the stowed or deployed solar awning

- In discussions with the participant, we determined that a stowed awning, represented as flush with the towed home surface, would allow for sufficient modeling accuracy while significantly reducing computational cost and meshing efforts.

Figure 1 illustrates the arrangement identified in this task, with simplified geometry provided by the participant.

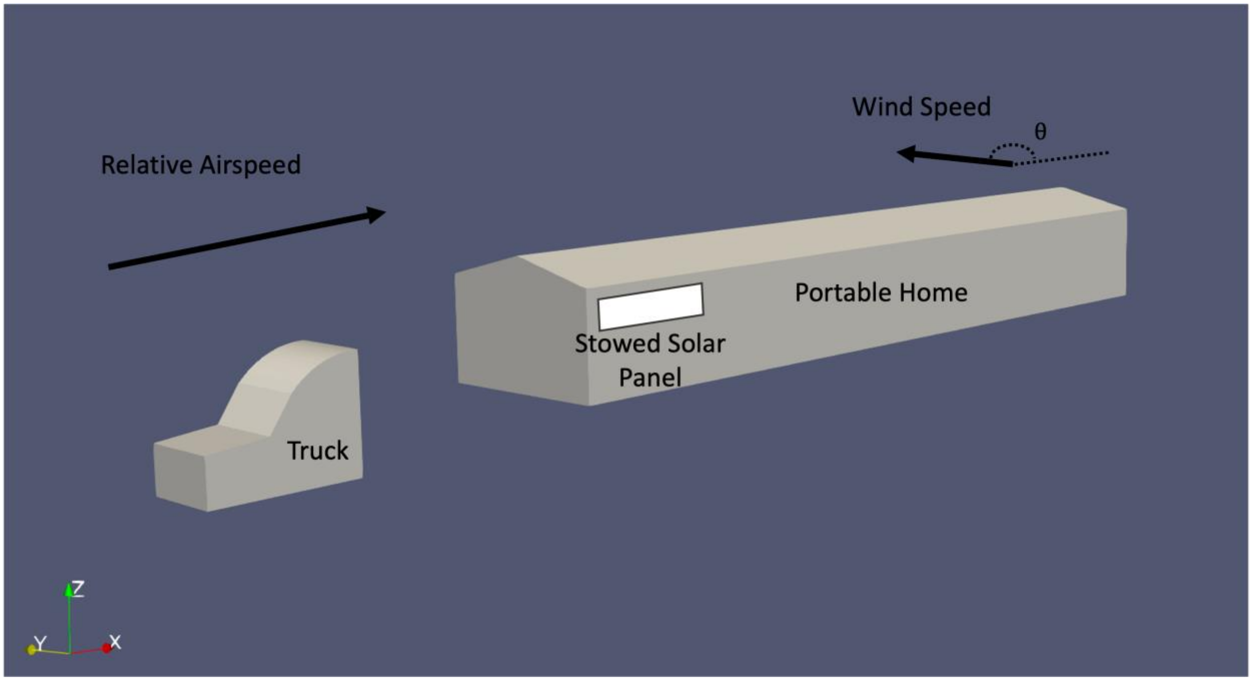


Figure 1. Truck assembly in transit.

Task 2: CFD Meshing

Subtask A: Import Solidworks CAD geometries into meshing software, e.g., Pointwise

- The participant provided a simplified CAD model of a truck with a home in tow, where the home is 9 ft 9 in tall, 7 ft wide, and 67 ft long. For simplicity, the truck is considered flush with the road, and the stowed solar panels are considered flush with the home structure. This is displayed in Figure 1 above.

  Subtask B: Generate a 3D body-fitted grid around semi-truck, house, and awning geometries of interest

- Near the solid bodies, the computational grid cell sizes were refined to have a wall-normal spacing of y+ = 1, as the RANS models require, and the mesh was extruded to larger cell sizes farther away. Figure 2 displays the body-conforming mesh, which was placed into a larger, block-structured mesh for overset simulations. The mesh was created with Pointwise.

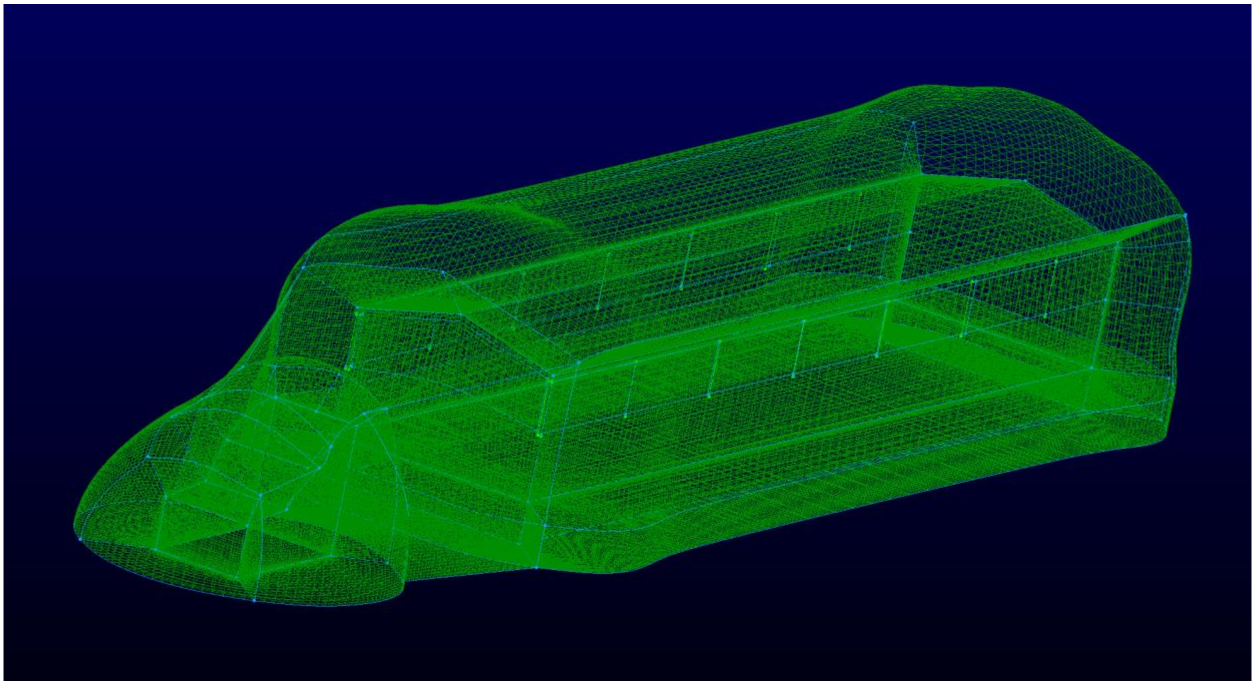


Figure 2. Body-conforming mesh surrounding truck assembly.

- On the mesh, to estimate the loading on stowed panels, a series of surfaces on the home were designated, and the forces exerted by the flow was measured on each surface. These consisted of surfaces on the “right” side of the structure, which becomes the upwind side when the ambient wind is at a nonzero angle, and the “left” side of the structure, which becomes the leeward side. Smaller surfaces were also defined at the front of the structure to measure the loading on the side of a stowed awning. Figure 2 shows the layout of these surfaces on the home structure. The surfaces are all 40 in tall, the side surfaces are 120 in wide, and the front surfaces are 4 in wide. These dimensions were chosen to correspond to the design of a Portable Solar awning. Figure 3 shows the arrangement of these sampling surfaces.

  Subtask C: Iterate on domain size and volume meshing parameters

- In the meshing process, the outer domain size was expanded to reduce blockage effects. The mesh cells near the boundary were confined to the needs of the turbulence models, and the other aspects of the mesh were tuned for stability and efficiency. Further iteration of the mesh was not necessary.

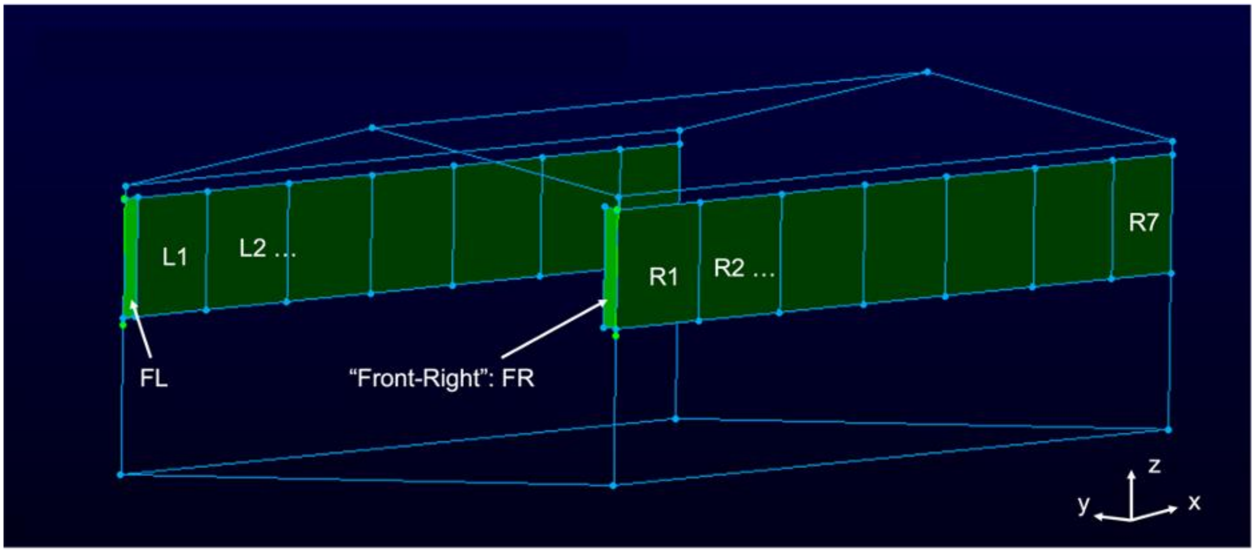


Figure 3. Sampling surfaces, representing solar panels, on towed home structure

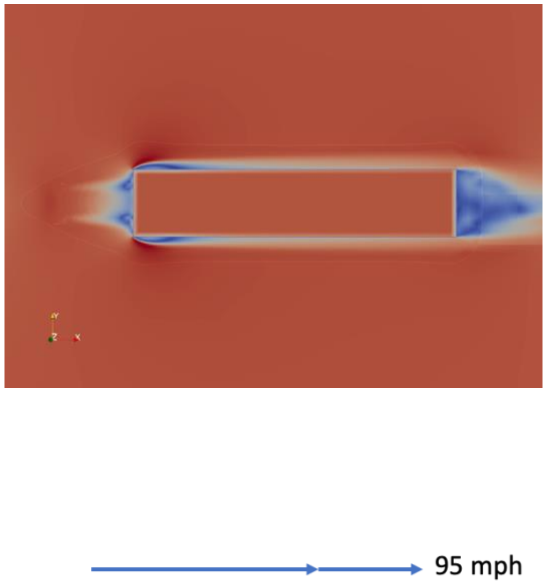
Task 3: Grid Convergence

Although we began efforts on a grid convergence study, the participant asserted that the measured loads from the initial study were too low to warrant further study. Furthermore, the participant began a lengthy redesign process at this time and requested work to be paused. For the runs that were completed, the simulations were run over several flow-through times to ensure that initial transients were not a factor in the results.

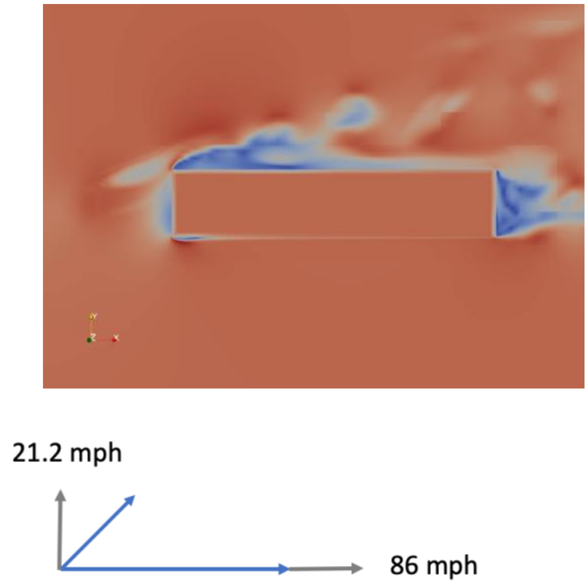
Task 4: Stowed PV Analysis

Subtasks: Simulate selected test conditions, assuming stowed panels are flush with the sides of the house; postprocess wind loading on simulated surfaces; visualize flow field around house and awnings.

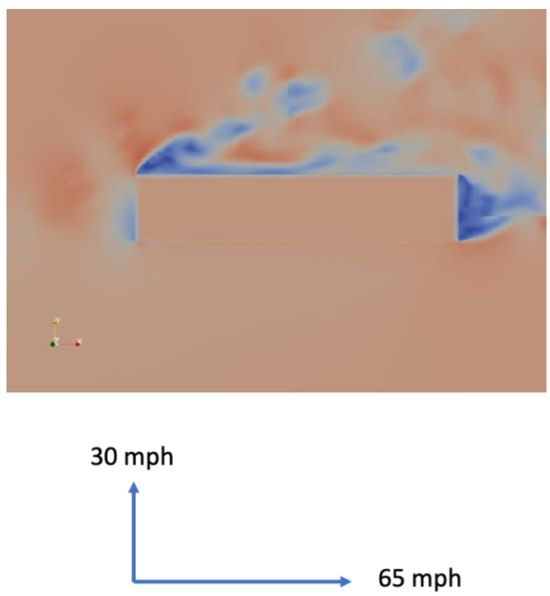
At an ambient wind angle of 0 degrees, the flow features a stagnation region at the front of the home in the wake of the truck, and then it accelerates around the front edges of the home, eventually creating a strong wake behind the home. As shown in Figure 4, flow structures remain small and no vortex shedding is visible near the panels. Increasing the ambient wind angle to 45 degrees leads to vortex shedding on the leeward side of the home, lessens the stagnation region at the front of the home, and smooths the flow on the windward side of the home. Increasing the angle again to 90 degrees amplifies these effects further while also decreasing the flow acceleration at the edges of the home, reducing the maximum velocity observed.



(a) 0°



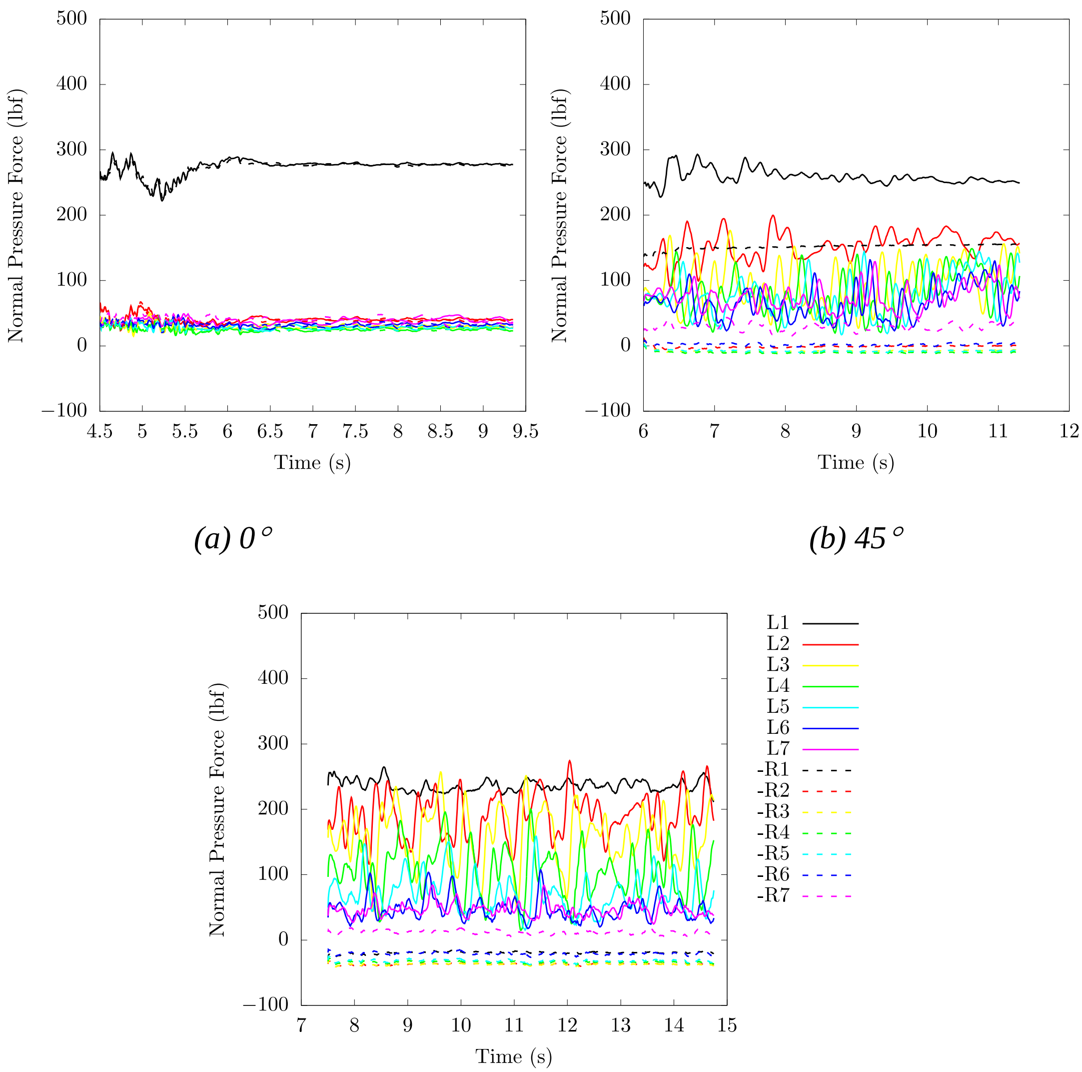
(b) 45°



(c) 90°

Figure 4. Horizontal plane showing velocity magnitude at a height of 9.8 ft off the ground (height of the panel). Red corresponds to 112 mph, and blue corresponds to 0 mph.

Figure 5 and Figure 6 show the loading as a function of time. Because of the flush representation of the panels, the normal force, as caused by the pressure distribution in the flow, is the most significant loading that can be measured. The maximum normal force observed on the side surfaces across the 3 cases is 300 lb-ft. When the ambient wind is at 0 degrees, only the first surfaces, near the front of the home, feel significant loading. As the angle changes, the forces felt by the leeward panels ("L") increase, and the forces felt by the windward panels ("R") decrease. The wind angle also introduces more transient loading, with variations up to 100 lb-ft at frequencies of about 3 Hz. The loading on the smaller front surfaces is much smaller. The magnitude depends on the ambient wind angle, but the forces remain less than 10 lb-ft and do not feature significant unsteady behavior.

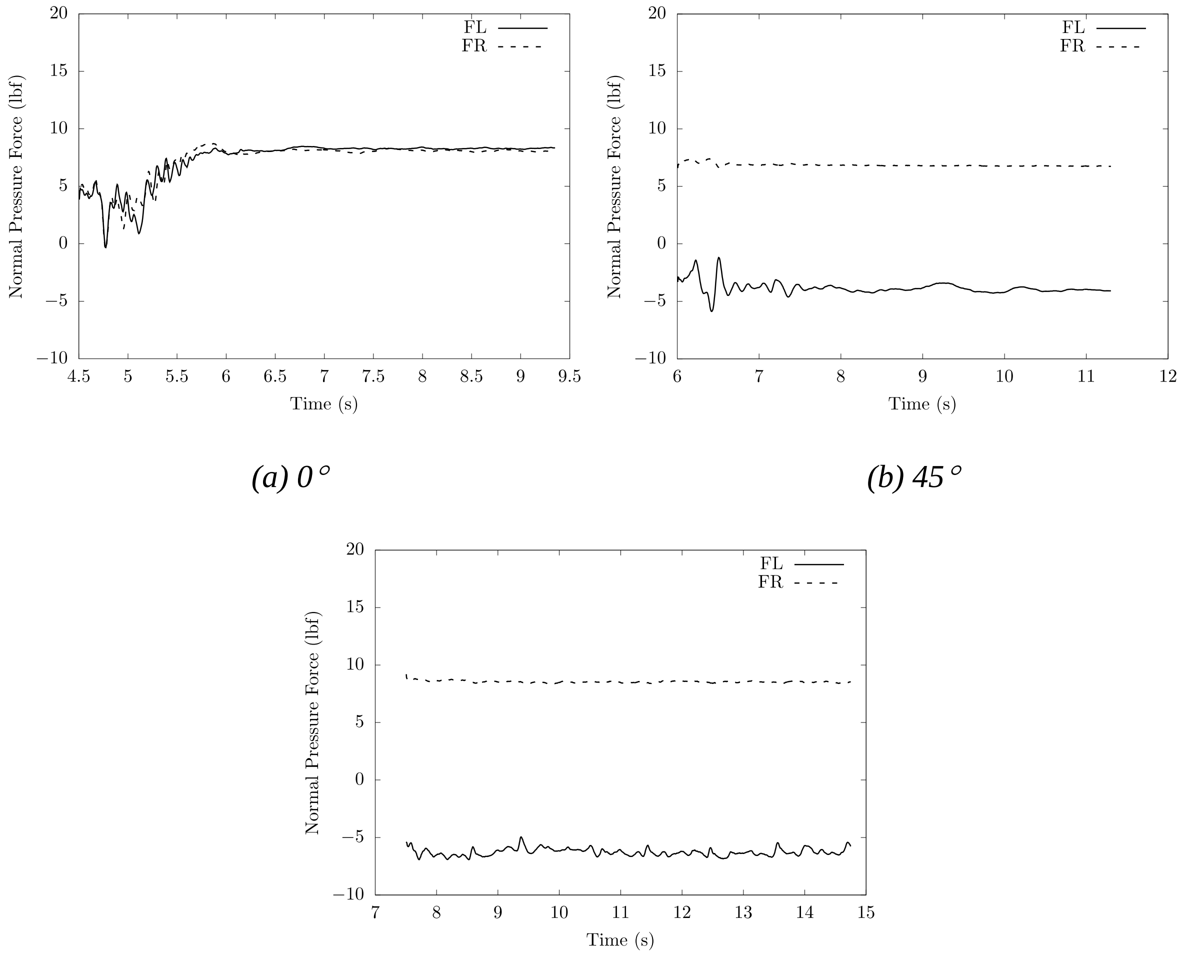


(a) 0°

(b) 45°

(c) 90°

Figure 5. Normal force on side sampling surfaces as a result of pressure in the flow



(a) 0° *(b) 45°* *(c) 90°*

Figure 6. Normal force on front sampling surfaces as a result of pressure in the flow

Task 5: Reporting

Subtasks: Summarize results; identify topics for further analysis.

The results from Task 4 were shared with the participant in a concise report. The participant concluded that this configuration did not warrant further study because the measured loads were much less than the limitations of the design. After a delay due to a redesign process, the participant determined that the best use of the remaining funds would be to evaluate the aerodynamic loads on the awning while deployed, not in transit.

Task 6: If appropriate, publish CFD results in a suitable journal or conference proceedings

By omitting the mesh convergence study, the results from this project lack the rigor required to publish in a suitable journal. The remaining funds were spent for further analysis in a different configuration, preventing conference opportunities.

Task 7: If funding permits, some field testing of an awning prototype at or near the Flatirons Campus

There was insufficient funding for field testing.

Task 8: NREL will prepare a CRADA Final Report: Preparation and submission in accordance with Article X.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X. Tasks 1-7 are from the initially agreed scope of work and the following tasks were also completed according to the discretion of the participant with the remaining funds.

Task 9 (added): Simulate deployed panels in wind loading conditions, mounts flush with structure

In addition to encountering wind loading during transit, these solar awnings will undergo significant wind loading due to weather. With the remaining funds in the project, we determined to evaluate the loading occurring while the awning is deployed. Evaluating the design in a deployment scenario adds certainty to the original design parameters from engineering standards.

The solar panel assembly, which has been simplified to a rectangular block, is mounted 10 ft above the ground to a rectangular structure with dimensions 40ft long, 13.5ft tall, and 16ft wide. The assembly is installed in the middle of the long side of the structure. Two deployment angles are considered: 0 degrees from the horizontal plane (90 degrees from the structure), and 45 degrees. Two assemblies were considered: a single panel and a grouping of three panels flush to each other. Wind speeds of 70, 100, and 130 mph were considered. Seven wind directions were tested, varying the horizontal and vertical angles by increments of 45 degrees, which are listed in Table 1 and shown in Figure 7 for clarity.

Table 1. Wind direction cases

Case	1	2	3	4	5	6	7
Horizontal	0°	0°	--	45°	45°	90°	90°
Vertical	0°	45°	90°	0°	45°	0°	45°

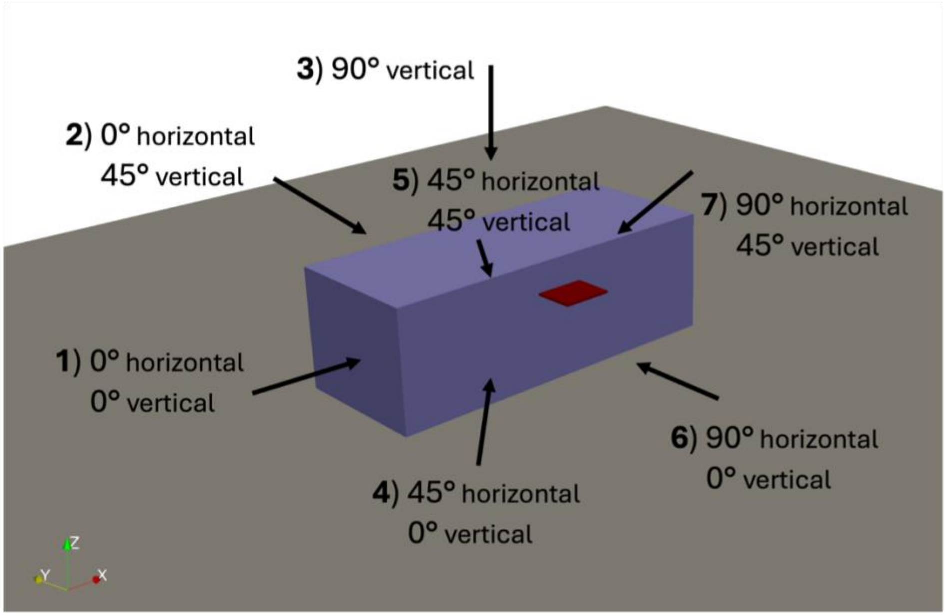


Figure 7. Diagram of wind direction cases with panel-structure assembly

To design this computation mesh, the bulk of the domain was meshed with structured cells, with the highest resolution applied in the vicinity of the panel(s). To connect the inner mesh around the panel to the outer mesh of the rest of the domain, unstructured meshing techniques were applied, and Figure 8 shows this approach. As a result, the flow can be represented as a single mesh assembly. To complete the simulations in this phase, four different meshes were created: one for a single panel deployed at 0 degrees, a single panel at 45 degrees, and three panels at each deployment angle. The overset approach was initially attempted for this flow, but it was found to be too inflexible to represent the problem well and converge to a solution.

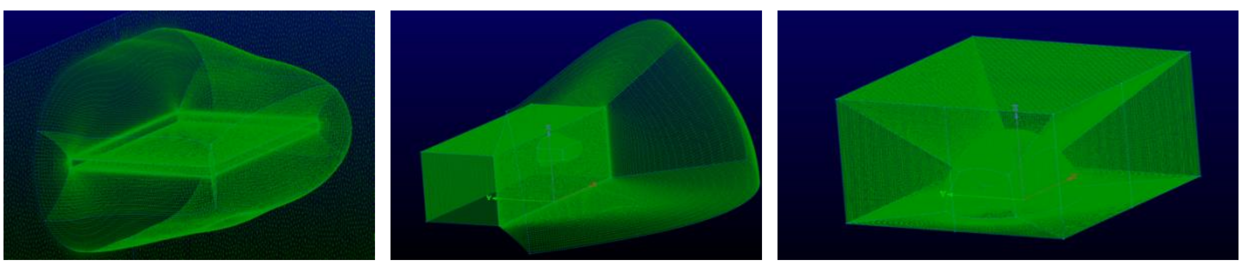


Figure 8. Meshing approach. From right to left: the high-resolution hexahedral mesh surrounding the deployed panel; the intermediate mesh block populated with unstructured cells, and the full mesh for the domain.

Visualization of the flow field reveals that Case 7 leads to a circulation region below the solar awning while part of the flow is diverted over the awning and the structure, as shown in Figure 9. These flow features combine to amplify the upward force on the awning. Further away from the awning, the flow accelerates as it is diverted around the structure, as shown in Figure 10. For Case 5, the first panel experiences a strong detached boundary layer, amplifying its loading compared to the other panels, as shown in Figure 11.

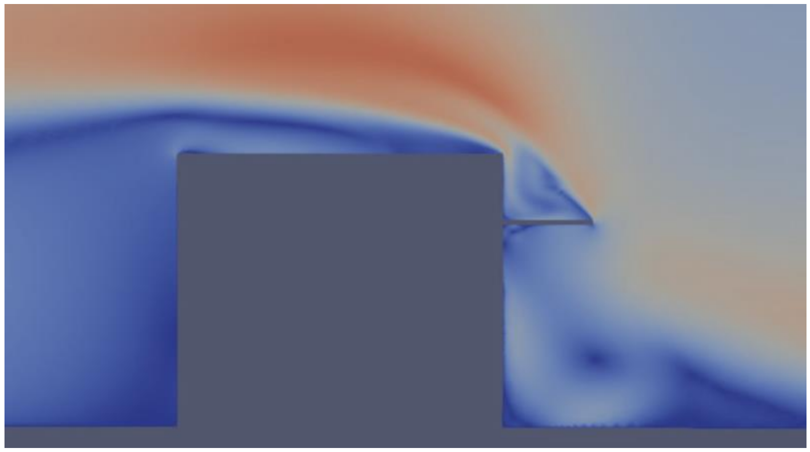


Figure 9. Slice in x of the flow at the center of the awning for Case 7, 130 mph. This simulation contains a single panel, and this image was captured after 5 seconds. Red represents 290 mph, and blue represents 0 mph.

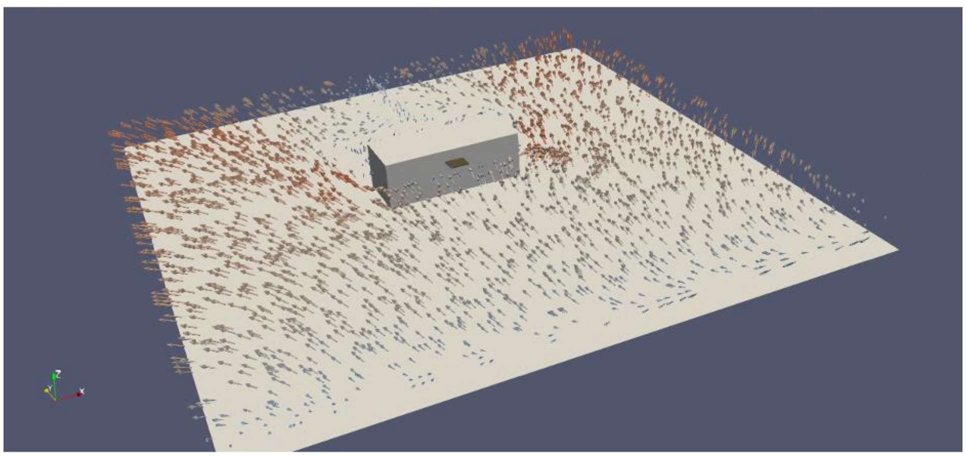


Figure 10. Vector field showing the flow at a height between the awning and the ground for Case 7, 130 mph. The length and color of the arrows correspond to the wind speed, with red representing 335 mph and blue representing 0 mph.

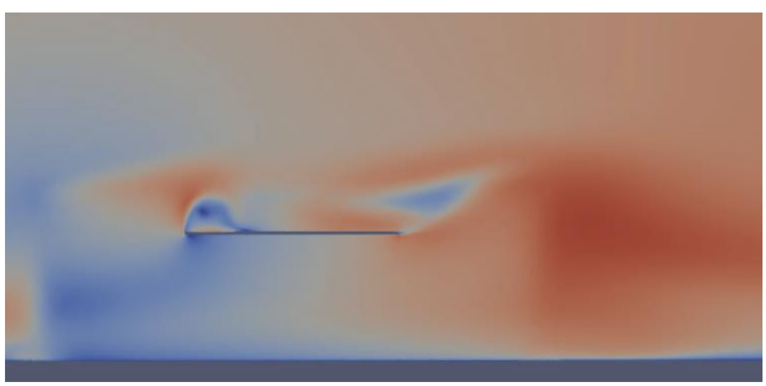


Figure 11. Slice in y of the flow at 1 ft from the structure for Case 5, 130 mph. This simulation contains three panels, and this image was captured after 5 seconds. Red represents 220 mph, and blue represents 0 mph.

During the simulations, the forces and moments on the panel assembly were recorded. After an initial transient, the average values were taken, and these average moments are reported in the figures below. As shown in Figure 12, the strongest loading caused by the wind are moments in the negative x direction, which push the panel assembly upward toward the mounting structure. These moments, and the loading in general, are insignificant when the wind direction is parallel to the x direction (cases 1-3) but grow to about 2000 lb. ft when a horizontal angle is introduced (cases 4 and 6), and grow further when a downward angle is added, reaching about 3500 lb-ft in case 5 and about 4000 lb-ft in case 7. Results for different deployment angles and 3-panel assemblies were provided to the participant but are omitted from this report for brevity. The deployment angle does not significantly alter the loading in most cases. For the 3-panel assemblies, the first panel (on the -x side) tends to experience the strongest loading, about 7000 lb-ft, which is greater than the single-panel case. In case 5, the other panels are shielded by the first panel, reducing the moment in x. In case 7, the central panel experiences a weaker moment (5000 lb-ft) compared to the panels on each side (6000 lb-ft). When the wind speed is decreased to 100 mph and 70 mph, the loading decreases as expected. This change correlates with the wind speed squared.

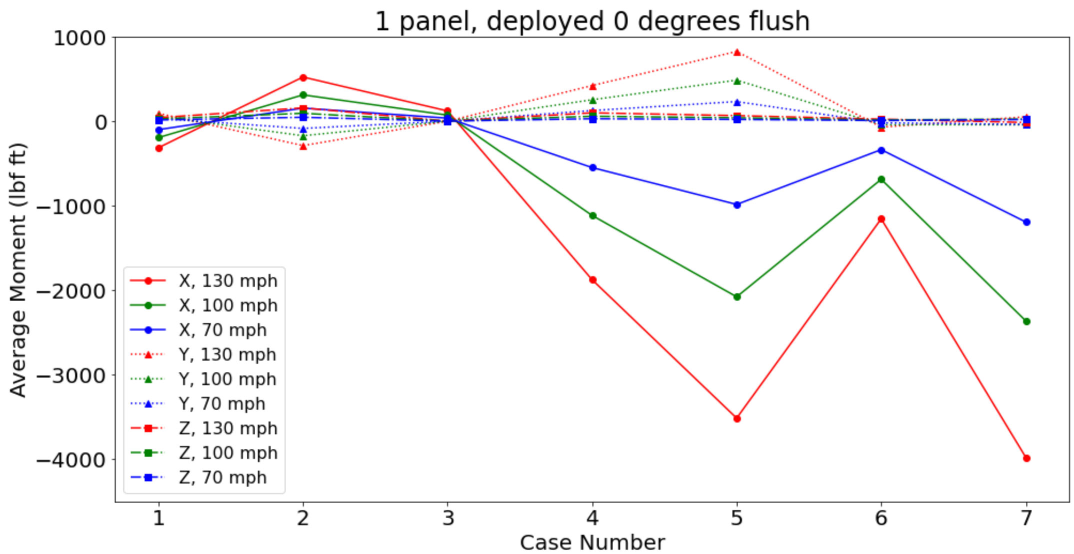


Figure 12. Average moments for each wind direction case with varying wind speeds

Task 10 (added): Simulate deployed panels in wind loading conditions, mounts spaced from structure

To make the simulation more realistic, a 9-inch gap was introduced between the awning and the structure. In the three-panel case, gaps of 1-inch were introduced between the panels. To focus on a single, realistic wind speed, this final set of simulations used 115 mph. The moment for each panel was calculated about the midpoint of the panel in x, the y coordinate on the panel closest to the structure, and the midpoint of the panel in z, as shown in Figure 13.

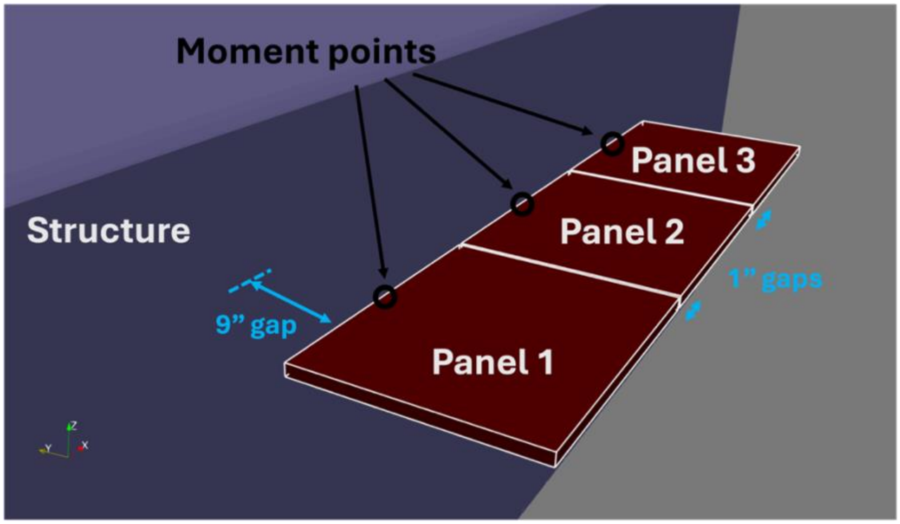


Figure 13. Depiction of the gaps in between the panels and the structure, as well as the points used for the moment calculations.

Visualizations of the flow show acceleration through the gaps, which is much more noticeable in the 9 in gap between the awning and the structure, is shown in Figure 14. The gaps between the panels do not have much of an effect on the flow due to their small size. Overall, the flow is comparable to the results without the gaps, but a direct comparison between the snapshots is not exact because of differing inflow wind speeds.

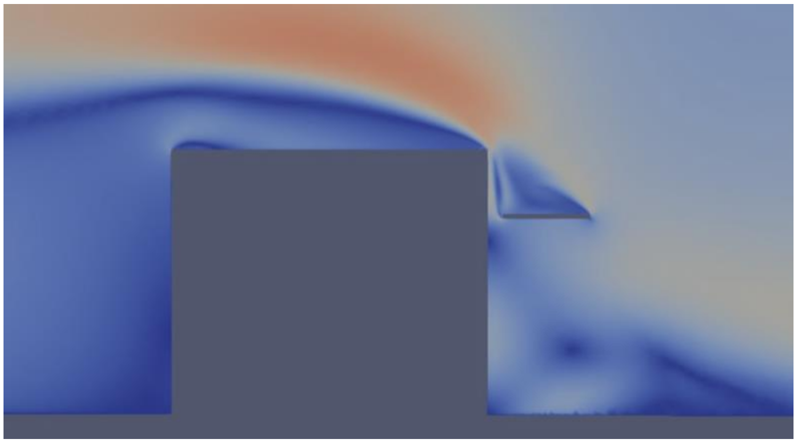


Figure 14. Slice in x of the flow at the center of the awning for Case 7, 115 mph. This simulation contains a single panel, and this image was captured after 5 seconds. Red represents 290 mph, and blue represents 0 mph.

Similar to the results without the gaps, the strongest moments caused by the wind are in the negative x direction, which push the panel assembly upward toward the mounting structure. These are shown in Figure 15. Compared to the results in the previous study, the introduction of gaps between the structure and the panels and between the panels does not make a noticeable change to the loading on the panel.

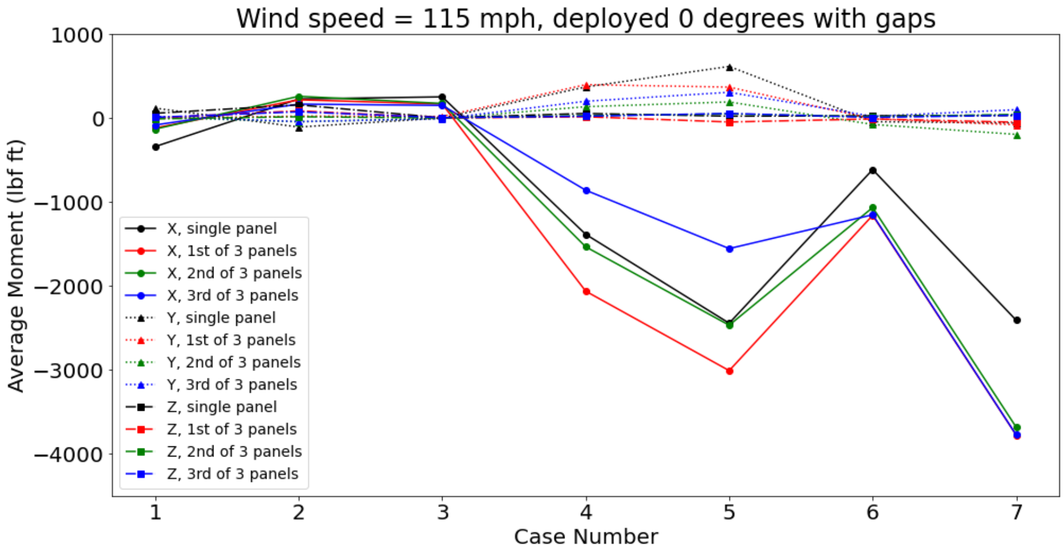


Figure 15. Average moments for each wind direction case with differing numbers of panels.

References:

1. Sharma A, Brazell MJ, Vijayakumar G, et al. "ExaWind: Open-source CFD for hybrid-RANS/LES geometry-resolved wind turbine simulations in atmospheric flows". *Wind Energy*. 2024; 27(3): 225-257. doi:10.1002/we.2886

Subject Inventions Listing:

None

ROI #:

None