SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Solar Collector Systems
https://doi.org/10.52825/solarpaces.v1i.726

Published: 16 Jan. 2024

Heliostat Consortium: Gap Analysis on Wind Load for Achieving a Fully Competitive Heliostat Industry

Matthew Emes[1][https://orcid.org/0000-0003-4147-4387], Shashank Yellapantula[2], Jeremy Sment[3], Kenneth Armijo[3], Matthew Muller[2], Mark Mehos[2], Randy Brost[3], and Maziar Arjomandi[1]

[1] The University of Adelaide, Australia

[2] National Renewable Energy Laboratory, United States

[3] Sandia National Laboratories, United States

Abstract. The Heliostat Consortium (HelioCon) Wind Load Subtask was initiated with the aim of bringing research work pertaining to wind load measurement, characterization, and prediction taking place across several tasks, including Advanced Manufacturing, Components and Controls, and Field Deployment. The cross-cutting wind load subtopic in the HelioCon roadmap report [1] highlighted standardized methods and tools that are needed for a more detailed understanding of the static and dynamic loads on a heliostat. This will enable cost reduction of wind-dependent heliostat components to avoid unnecessarily conservative, overly constrained designs and increase field efficiency/reliability, to reduce the risk of component failures due to high-wind events (>15 m/s). Gaps related to heliostat wind load include site characterization for wind measurements, critical load cases for heliostat design, turbulence impacts on heliostat tracking error, testing of heliostat array configurations, understanding spatial variation of maximum loads across the solar field, and heliostat field layout and operating strategies. The recommended highest-priority pathway as first steps taken by HelioCon to address these gaps are to develop site characterization guidelines for heliostat design and field load measurements.

Keywords: Aerodynamic Coefficients, Turbulent Flow Field, Structural Dynamics, Heliostat Wind Load

1. Introduction

Heliostat fields are generally located on open terrain within the atmospheric boundary layer (ABL), which imposes unsteady loads on heliostat drives, torque tube, pylon, foundation, as well as mirror mechanical support components. The wind load bearing heliostat components are designed for two conditions:

1. Serviceability with required stiffness to minimize local deformations and displacement of the mirror surface during operation (Figure 1a), typically with a maximum slope error in the order of 1 mrad at all orientations.
2. Survivability with sufficient strength to resist the maximum loads during high-wind events, either in operation or when the heliostat surface is aligned horizontally in the stow position (Figure 1b).

Static wind loads on heliostats are conventionally determined using non-dimensional aerodynamic coefficients that account for the heliostat shape depending on the structural design and ABL turbulence due to the surface roughness of a field site. Wind load coefficients are used in combination with stow and survival design wind speeds to estimate the bending and torsional loads at the hinge and base of the heliostat pylon resisted by the torque tube, pedestal, and foundation.

Dynamic wind loads, induced by coupling between transient wind fluctuations and dynamic properties of the heliostat reflective structure, unsteady pressure distributions and oscillations of the heliostat surface, impact tracking accuracy and overall optical performance of the heliostat field [2, 3]. Detailed understanding of the static loads and dynamic response of a heliostat design with respect to the local wind conditions at field sites are critical to:

1. Reducing conservative manufacturing safety factors, tolerances and material cost.
2. Increasing field efficiency and reliability and thus reduce risk of component failures due to high-wind events.
3. Maximizing energy production by reducing wind-induced production loss.

Determination of accurate heliostat design loads for site-specific low-altitude wind characteristics are important to reduce uncertainty and increase confidence in heliostat performance measures with a potential to reduce finance risk, O&M and replacement costs. However, such favorable outcomes may be offset by repeated non-reoccurring engineering costs and component validation if each site requires different designs or components based on site-specific typical meteorological year (TMY) weather analysis.

The layout of heliostat fields in power tower plants have been optimized primarily with respect to the optical efficiency of a field, which generally doesn’t account properly for wind load [2]. Design wind loads are usually determined on a single isolated heliostat in operating positions (Figure 1a) and stow position (Figure 1b) parallel to the ground during high-wind conditions. Within a heliostat field (Figure 1c), the mean flow and turbulence characteristics can be significantly different from the incoming atmospheric flow. The wind loads on heliostats in a field therefore vary from those of a single heliostat conventionally adopted for uniform field design to counter increases in manufacturing cost and quality deviation of multiple heliostat designs in a field.

(a) (b) (c)

Figure 1. Flow field aerodynamics and wind loads vary between (a) operating positions and (b) horizontal stow position for individual heliostats and (c) heliostats in field arrangements. Photographs taken by Matthew Emes at the Plataforma Solar de Almeria (PSA), Spain.

2. State of the art in heliostat wind load

Heliostat wind load measurement, characterization and prediction have been identified by various industry, academic and government stakeholders as a crucial design consideration in review studies for CSP best practices [4, 5]. Current best practice is static and dynamic load measurements on scale-model heliostats in boundary layer wind tunnels to characterize controlled wind loading through non-dimentionalized coefficients and surface pressure distributions as inputs to finite element analysis (FEA) models and analytical approaches based on wind codes for buildings with fundamental natural frequencies smaller than 1 Hz [6, 7]. Full-scale prototype testing also exists for dynamic load analysis but is scarcely published in the literature. Development of computational fluid dynamics (CFD) models to complement wind tunnel and field measurements is ongoing, however they are computationally expensive with limited capability to accurately reproduce practical atmospheric wind conditions and resolve small-scale turbulence structures of relevance to operational heliostat wind loads.

2.1. Static and dynamic wind load measurement and modelling techniques

Heliostat design methods for aerodynamic load coefficients pioneered by Peterka *et al.* [8] considered the effect of longitudinal turbulence intensity on peak wind loads [9]. Part-depth atmospheric boundary layer simulations in wind tunnels have been established by the German Aerospace Center (DLR) and the University of Adelaide for wind load analysis on scale-model heliostats based on dimensional analysis and similarity of turbulence spectra and force balance techniques [5, 10, 11]. Field measurement techniques for dynamic wind loads have been established by Sandia National Laboratories and German Aerospace Center through mode shape and frequency analysis on vortex shedding, beam deviation and tracking error [3, 12, 13]. The state of the art techniques for wind load measurement on heliostats include:

- High-frequency force balance method (at up to 1 kHz) for determining wind load coefficients of drag forces and base overturning moments.
- Integration of surface pressure distribution through pressure taps on upper and lower surface (at up to 1 kHz) are commonly adopted for lift forces, hinge moments and dynamic load analysis.
- Strain gauges, load cells, and accelerometers are robust and can be mounted on full-scale heliostats in atmospheric conditions to characterize dynamic heliostat behavior. Load cells (at up to 1 kHz) provide three-dimensional force and moment measurements and offer robust operation in outdoor conditions.
- Dynamic strain gauges offer high sensitivity (500 mV/g) measurements of strain with accurate frequency and damping characteristics even at low wind speeds [12].
- Tri-axial accelerometers identify mode shapes and frequencies of a heliostat structure and dynamic response through hammer-excited and wind-excited testing [3].
- Multi-camera dynamic photogrammetry techniques offer increased resolution of wind-induced dynamic response of Stellio heliostat at low frequencies [13].
- Beam characterization system (BCS) measurement of wind-induced aiming error [14].

Matching of turbulence spectra in the reduced frequency range corresponding to full-scale load distributions provides consistent maximum relative load distributions [15, 16]. Integral length scales of the turbulent eddies in the atmospheric surface layer relative to the heliostat structure characteristic length correlates strongly with maximum wind loads in stow position [17], and at a 90 degree elevation [18]. Heliostat models with a geometric scaling ratio of 1:20 show similarity of longitudinal spectra for operating loads, whereas a scaling ratio of 1:60 with smaller dimensions show similarity of vertical spectra for stow loads [5]. Square-mirrored heliostats are subject to smaller torsional loading than PV arrays, but azimuth moments and lift forces increase with increasing heliostat mirror aspect ratio [10]. Single heliostat structure CFD models of heliostats have been investigated to complement wind tunnel studies on rigid/static behavior of structures. These are mostly steady RANS based simulations with restricted generation of turbulent inflow conditions. Unsteady simulations with complex array configurations are computationally expensive and are being used sparingly to study deep array effects on collector structures [2, 19, 20].

2.2. Atmospheric Boundary Layer characterization at heights relevant to heliostats

Wind characterization is crucial at site selection. In practice during operation of a CSP central receiver field, heliostats are stowed based on a 3-second gust wind speed [3]. The moving average gust speed over 3 seconds at a 10 m height, defined by the World Meteorological Organization, is adopted by most national weather services and measured by cup anemometers (1 Hz) at automatic weather stations. Second-generation heliostats defined with a maximum operational design gust wind speed of 22 m/s and a stow survival design wind speed of 40 m/s at a 10-m height based on a 100-year mean recurrence interval [21]. Heliostat design wind speeds for maximum operating and stow configurations are specified using local/regional wind maps in national wind codes with limited frequency and resolution of historical wind measurements at the proposed field site. Strategies for stowing heliostats are conventionally applied uniformly to the entire, or subsets, of a heliostat field based on point measurement of wind gust velocity at or near the field site [22]. Annual CSP field efficiency models conventionally input TMY hourly or daily averaged wind data [5].

Mesoscale simulations performed using a numerical weather prediction model, such as weather research and forecasting (WRF), typically contain key atmospheric flow physics and are designed to reproduce dynamic features in the atmosphere. Mesoscale simulations have been advanced significantly in the last couple of decades and are being used to predict synoptic and mesoscale processes associated with extratropical cyclones, fronts, and jets. These mesoscale weather models also include techniques to assimilate a wide range of direct and indirect observation types, from traditional in situ surface and upper-air data to satellite-based measurements [23]. Mesoscale WRF models were developed using data from neutral stability conditions and sparse field measurements over large domain sizes with horizontal grid resolution on the order of 1 km. However, increased spatial resolution on the order of 10 m is needed to accurately represent the complex terrain features and similarity functions in the atmospheric surface layer [24] and thus resolve temporal wind fluctuations and turbulence length scales that impact heliostat wind loads.

2.3. Wind load predictions and reduction techniques in the field

Wind load predictions using aerodynamic coefficients on single heliostats in different roughness terrains (and therefore turbulence levels) are commonly applied to stress analysis equations and FEA models for sizing of the pedestal, torque tube and foundation and sensitivity analysis of weight and cost of structural components under wind loads on heliostats of different sizes. The impact of shielding and blocking effects on reduced static loads and dynamic amplification effects on in-field heliostats needs to be quantified with synchronous load and flow measurements in a heliostat field. This is complicated by time-varying heliostat configurations. The shielding effect for wind protection and dust mitigation has been investigated and adopted using perimeter fences in heliostat fields. Reductions in wind speed and turbulence of the incoming atmospheric boundary layer can be achieved using fences; however, the porosity and height of fence required to be effective in a field of heliostats requires further investigation [25]. Retrofit devices mounted to the edge of a heliostat present an alternative method to reduce loads and internal mass reduction of heliostats on the inner field similar to that adopted in parabolic trough fields [4] requires further feasibility and techno-economic analysis.

3. Wind load gap analysis

The top-ranked highest-priority gaps on wind load in Table 1 would have an impact on heliostat technology deployment, and eventually the growth of the heliostat industry, if not addressed.

To neglect these gaps would significantly increase risks related to the performance and financing of CSP projects.

Based on preliminary assessment of data available from published studies and parametric analysis of turbulence-load correlations, it has been estimated that wind site characterization (WL1) is of significant impact to design loads and cost of heliostats. Considering average turbulence intensities and length scales at field sites ranging from flat desert to open country terrains and noting the lack of standards for defining a gust load event and design wind speed specifications, the estimated maximum reduction of 10% (\$13/m^2) in total heliostat installed cost corresponds to an LCOE reduction of 3% with respect to a baseline commercial heliostat installed cost of \$140/m^2 [26]. This justifies effort toward advanced wind characterization techniques for design wind speed and load evaluation at site selection.

Better understanding of wind turbulence parameters and their impact on the fluctuating component of tracking error (WL2) are estimated to provide a cost benefit through approximated savings of up to \$5/m^2 on drive systems of small heliostats without adversely impacting field performance. However, maintaining high-accuracy actuation systems in state-of-the-art heliostat designs to drive field performance improvements may also necessitate structural steel component wall thickness to be adapted for changes in wind conditions.

Wind loads on heliostats in fields (WL3) are strongly dependent on heliostat field density, or the non-dimensional spacing between the heliostats with respect to the mirror chord (windward) length. Shielded inner rows at high field density can be subject to considerably lower mean wind loads while simultaneously facing less stringent pointing and beam quality requirements due to their proximity to the tower. This may allow the design of lighter in-field heliostats with a larger allowable deflection under reduced wind loads while delivering adequate performance. However, the peak wind loads in high-density field regions can be increased above those on a single heliostat, such as a 30% increase in lift forces on a heliostat in stow [27] and a 40% increase in maximum operating hinge moment [28]. Such load amplifications for limiting cases are likely to be caused by the increased unsteadiness of flow in the wake of upstream operating heliostats at distances up to 8 chord lengths [29] and increased centre of pressure movement further from the central elevation axis than in the case of a single heliostat [28]. Load variation within heliostat fields is not well understood and difficult to characterize. Nevertheless, through measurements on instrumented heliostats in field sectors and analysis of their deflection and its dependence on spatial relationships to other heliostats (and the tower), analytical models of wake flow interactions and load distributions may be developed and combined with dynamic performance impacts.

Using data available from published wind tunnel studies, it has been estimated that design standards for determining design wind load coefficients and safety factors (WL4) is of crucial importance. Considering the uncertainties of scaling model data in wind tunnel experiments to full-scale designs and conservative extreme value analysis methods to estimate maximum wind loads corresponding to the range of critical load case heliostat configurations, we tentatively estimate an LCOE reduction at least equivalent to WL1 with decreased total heliostat installed cost and increased energy production. Standardized approaches that focus on heliostat structural shapes and their dynamic behavior would contribute to more flexible stow strategies and improved accuracy of peak wind load estimations compared with conservative predictions using standards for buildings.

Table 1. Highest priority gap analysis on wind load.

Gaps	Addressing Strategy	Recommended Pathway
WL1: Insufficient wind measurement and	• To provide recommendations and guidelines for the required	• Analyse high-frequency DNI and wind data, define site

characterization at heliostat field sites	equipment and data collection and processing techniques	characterization ABL modelling parameters • Wind characterization guidelines (SolarPACES, IEC) for ABL site assessment of wind loads and publicly available database
WL2: Lack of understanding on the impact of atmospheric turbulence on dynamic loading and tracking error	• To investigate the correlation between tracking error, field layout, and terrain roughness	• Correlate wind fluctuations with heliostat tracking and slope error • Correlate wind fluctuations with receiver thermal energy capture and flux distribution
WL3: Lack of understanding of wind load on heliostats in array configurations	• Wind tunnel experiments and computational fluid dynamics modeling to develop correlations between heliostat wake and load data on array configurations	• Characterize loads on arrays of heliostats in wind tunnel and CFD simulations and publish results in journals and international conferences • Analyse and publish wind load coefficients comparing wind tunnel experiments and field measurements
WL4: Missing design standards for determining heliostat wind load coefficients and safety factors	• Guidelines for industry to apply testing procedures for deriving ultimate wind loads on different heliostat designs • Safety factors for static loads and dynamic response of heliostat with respect to site wind speed and turbulence conditions	• Investigation of the relationship between gust factor and wind speed standard deviation, and peak loads on heliostat structures • In collaboration with industry, review and develop procedures through initial design and prototype testing

4. Conclusions and future work

The HelioCon wind load subtask has developed two work plans: the first is to address gaps WL1 and WL4 to develop wind load and site characterization guidelines for heliostat design. The objective is to develop methodology and draft guidelines to convert wind measurement and load data into effective design decisions for spatially specific mass reduction of heliostat supporting structures. The second work plan is to address gaps WL2 and WL3 to develop heliostat field wind load models with optical performance impacts, with the objective of determining the impact of heliostat field wind loads on cost and field performance using relationships between dynamic tracking error, slope error, field layout, and terrain roughness. The approach proposed to complete these tasks includes wind tunnel and field measurements at the University of Adelaide Atmospheric Boundary Layer Research Facility (ABLRF) to correlate heliostat tracking angles and wind turbulence with wind loads. This will be complemented at the Sandia National Laboratories National Solar Thermal Test Facility (NSTTF) with in-field synchronous measurements of wind-induced optical slope error and tracking error effects on field thermal energy capture and flux distribution. National Renewable Energy Laboratory will develop a CFD model on wind loads on single heliostat validated against the University of Adelaide wind tunnel data and deep array effects validated against heliostat field data.

Data availability statement

Data supporting the gap analysis can be accessed by contacting the corresponding author.

Author contributions

Matthew Emes contributed to conceptualization, investigation, methodology and writing original draft. Shashank Yellapantula contributed to conceptualization, methodology and writing original draft. Jeremy Sment contributed to conceptualization, methodology and review. Kenneth Armijo contributed to conceptualization, methodology, review and editing. Matthew Muller contributed to conceptualization, methodology and review. Mark Mehos contributed to conceptualization, review and editing. Randy Brost contributed to conceptualization, review and editing. Maziar Arjomandi contributed to conceptualization, review and editing.

Competing interests

The authors declare no competing interests.

Funding

Funding for the HelioCon roadmap report development has been provided by the Department of Energy (DOE) Solar Energy Technologies Office. Australian Solar Thermal Research Institute (ASTRI) work has been supported through funding provided by Australian Renewable Energy Agency (ARENA) Grant 1-SRI002. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

Acknowledgement

The authors acknowledge the contributions of HelioCon and industry subject-matter experts for their input in developing the roadmap report subsection on wind load.

References

1. G. Zhu, C. Augustine, R. Mitchell, M. Muller, P. Kurup, A. Zolan, S. Yellapantula, R. Brost, K. Armijo, J. Sment, R. Schaller, M. Gordon, M. Collins, J. Coventry, J. Pye, M. Cholette, G. Picotti, M. Arjomandi, M. Emes, D. Potter and M. Rae, Advancing Heliostat Technologies for Concentrating Solar-Thermal Power: Heliostat Consortium (HelioCon) Roadmap (2022). https://doi.org/10.2172/1888029
2. A. Pfahl, J. Coventry, M. Röger, F. Wolfertstetter, J. F. Vásquez-Arango, F. Gross, M. Arjomandi, P. Schwarzbözl, M. Geiger and P. Liedke, Progress in heliostat development, Solar Energy 152, 3-37 (2017). https://doi.org/10.1016/j.solener.2017.03.029
3. D. T. Griffith, A. C. Moya, C. K. Ho and P. S. Hunter, Structural dynamics testing and analysis for design evaluation and monitoring of heliostats, Journal of Solar Energy Engineering 137, 021010 (2015). https://doi.org/10.1115/1.4028561.
4. M. Mehos, H. Price, R. Cable, D. Kearney, B. Kelly, G. Kolb and F. Morse, Concentrating solar power best practices study (National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020). https://doi.org/10.2172/1665767
5. M. Emes, A. Jafari, A. Pfahl, J. Coventry and M. Arjomandi, A review of static and dynamic heliostat wind loads, Solar Energy 225, 60-82 (2021). https://doi.org/10.1016/j.solener.2021.07.014
6. AS/NZS 1170.2, Structural Design Actions - Part 2: Wind actions (Standards Australia and Standards New Zealand, Sydney, 2011), pp. 26-41.

7. ASCE 7-02, Minimum design wind loads for buildings and other structures, American Society of Civil Engineers, Reston, Virginia, 2002, ASCE 7-02.
8. J. A. Peterka and R. G. Derickson, Wind load design methods for ground-based heliostats and parabolic dish collectors (Sandia National Laboratories, Albuquerque, New Mexico, 1992), SAND92-7009. https://doi.org/10.2172/7105290
9. J. A. Peterka, Z. Tan, J. E. Cermak and B. Bienkiewicz, Mean and peak wind loads on heliostats, Journal of Solar Energy Engineering 111, 158-164 (1989). https://doi.org/10.1115/1.3268302
10. A. Pfahl, M. Buselmeier and M. Zaschke, Wind loads on heliostats and photovoltaic trackers of various aspect ratios, Solar Energy 85, 2185-2201 (2011). https://doi.org/10.1016/j.solener.2011.06.006
11. M. Arjomandi, M. Emes, A. Jafari, J. Yu, F. Ghanadi, R. Kelso, B. Cazzolato, J. Coventry and M. Collins, A summary of experimental studies on heliostat wind loads in a turbulent atmospheric boundary layer, AIP Conference Proceedings 2303, 030003 (2020). https://doi.org/10.1063/5.0028676
12. C. K. Ho, D. T. Griffith, J. Sment, A. C. Moya, J. M. Christian, J. K. Yuan and P. S. Hunter, Dynamic Testing and Analysis of Heliostats to Evaluate Impacts of Wind on Optical Performance and Structural Fatigue, in: SolarPACES, AIP Conference Proceedings, Marrakech, Morocco, 2012, pp. 22695.
13. K. Blume, M. Röger, T. Schlichting, A. Macke and R. Pitz-Paal, Dynamic photogrammetry applied to a real scale heliostat: Insights into the wind-induced behavior and effects on the optical performance, Solar Energy 212, 297-308 (2020). https://doi.org/10.1016/j.solener.2020.10.056
14. J. W. Strachan, Revisiting the BCS, a Measurement System for Characterizing the Optics of Solar Collectors (Sandia Technical Report SAND92-2789C, 1992).
15. A. Jafari, F. Ghanadi, M. J. Emes, M. Arjomandi and B. S. Cazzolato, Measurement of unsteady wind loads in a wind tunnel: scaling of turbulence spectra, Journal of Wind Eng and Ind Aero 193, 103955 (2019b). https://doi.org/10.1016/j.jweia.2019.103955
16. A. Pfahl, M. Randt, F. Meier, M. Zaschke, C. Geurts and M. Buselmeier, A holistic approach for low cost heliostat fields, Energy Procedia 69, 178-187 (2015). https://doi.org/10.1016/j.egypro.2015.03.021
17. A. Jafari, F. Ghanadi, M. Arjomandi, M. J. Emes and B. S. Cazzolato, Correlating turbulence intensity and length scale with the unsteady lift force on flat plates in an atmospheric boundary layer flow, Journal of Wind Eng and Ind Aero 189, 218-230 (2019a). https://doi.org/10.1016/j.jweia.2019.03.029
18. M. J. Emes, A. Jafari, J. Coventry and M. Arjomandi, The influence of atmospheric boundary layer turbulence on the design wind loads and cost of heliostats, Solar Energy 207, 796-812 (2020). https://doi.org/10.1016/j.solener.2020.07.022
19. J. R. Wolmarans and K. Craig, One-way fluid-structure interaction of a medium-sized heliostat using scale-resolving CFD simulation, Solar Energy 191, 84-99 (2019). https://doi.org/10.1016/j.solener.2019.08.068
20. S. Yellapantula, G. Vijayakumar, D. Kesseli, S. Ananthan and M. Mehos, "Aerodynamic analysis of wind loading on parabolic trough collectors using high-fidelity CFD modeling," in AIP Conference Proceedings,(AIP Conference Proceedings, 2022), pp. 030023. https://doi.org/10.1063/5.0087124
21. L. M. Murphy, Wind loading on tracking and field-mounted solar collectors (Solar Energy Research Institute, Golden, USA, 1980), SERI-TP-632-958. https://doi.org/10.2172/6889663
22. M. Emes, A. Jafari, M. Collins, S. Wilbert, L. Zarzalejo, S. Siegrist and M. Arjomandi, Stowing strategy for a heliostat field based on wind speed and direction, AIP Conference Proceedings 2445, 120011 (2022). https://doi.org/10.1063/5.0085677
23. J. G. Powers, J. B. Klemp, W. C. Skamarock, C. A. Davis, J. Dudhia, D. O. Gill, J. L. Coen, D. J. Gochis, R. Ahmadov and S. E. Peckham, The weather research and forecasting model: Overview, system efforts, and future directions, Bulletin of the

American Meteorological Society 98, 1717-1737 (2017). https://doi.org/10.1175/BAMS-D-15-00308.1

24. P. A. Jiménez, J. Dudhia, J. F. González-Rouco, J. Navarro, J. P. Montávez and E. García-Bustamante, A revised scheme for the WRF surface layer formulation, Monthly weather review 140, 898-918 (2012). https://doi.org/10.1175/MWR-D-11-00056.1
25. M. J. Emes, A. Jafari and M. Arjomandi, A feasibility study on the application of mesh grids for heliostat wind load reduction, Solar Energy 240, 121-130 (2022). https://doi.org/10.1016/j.solener.2022.05.033
26. P. Kurup, S. Akar, S. Glynn, C. Augustine and P. Davenport, Cost Update: Commercial and Advanced Heliostat Collectors (National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022). https://doi.org/10.2172/1847876
27. A. Pfahl, M. Buselmeier and M. Zaschke, "Determination of wind loads on heliostats," in Proceedings of the 17th SolarPACES Conference,(Proceedings of the 17th SolarPACES Conference, Granada, Spain, 2011).
28. A. Jafari, M. Emes, B. Cazzolato, F. Ghanadi and M. Arjomandi, An experimental investigation of unsteady pressure distribution on tandem heliostats, AIP Conference Proceedings 2303, 030022 (2020). https://doi.org/10.1063/5.0028678
29. A. Jafari, M. Emes, B. Cazzolato, F. Ghanadi and M. Arjomandi, Turbulence characteristics in the wake of a heliostat in an atmospheric boundary layer flow, Physics of Fluids 32, 045116 (2020). https://doi.org/10.1063/5.0005594