ISEIS

Journal of Environmental Informatics Letters 12(1) 44-50 (2024)

Journal of Environmental Informatics Letters

www.iseis.org/jeil

An Analytical Study into the Impact of Wind Load on the Stability and Robustness of Solar Panel Support Structures

J. Parthipan[1 *], S. Manikandan[2], K. Sakthimurugan[3], and N. Kayalvizhi[4]

[1] *Department of Robotics and Automation, Sri Muthukumaran Institute of Technology, Chennai, Tamil Nadu 600 069, India*
[2] *Department of Civil Engineering, Sri Muthukumaran Institute of Technology, Chennai, Tamil Nadu 600 069, India*
[3] *Department of Civil Engineering, CK College of Engineering and Technology, Cuddalore, Tamil Nadu 607 003, India*
[4] *Department of Civil Engineering, Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu 600 073, India*

Received 20 Novermber 2023; revised 06 April 2024; accepted 06 May 2024; published online 15 September 2024

ABSTRACT. Renewable energy sources, including wind, hydro, solar, and tidal power, are experiencing a growing global focus. Given the escalating ubiquity of expansive solar arrays, it is crucial to prioritize the dependability and structural soundness of the supporting frameworks for solar panels. The current study examined the effects of different wind loads on the lateral stability of frames of support made for solar panels using the finite element approach. The research examined wind speeds ranging from 72 to 144 kmph, and the calculation of wind forces was performed using mathematical approaches. The results of our investigation demonstrate that wind loads significantly influence the structural soundness of solar panels, resulting in noticeable enhancements in total deformation and maximum equivalent stresses. The investigation findings indicate that the points of intersection within the supporting structure of the solar panel saw the highest levels of stress equivalence. Moreover, it was observed that the structural deformation exhibited greater prominence in the central and foundational areas. The research investigation has yielded valuable insights into the spatial patterns of stress and deformation, two critical parameters that play a pivotal role in the design, durability, and efficiency of support systems for photovoltaic modules. The implications of these findings carry considerable weight regarding the future progress of large-scale solar arrays, hence requiring further investigation to optimize the design and functionality of the supporting frameworks.

Keywords: finite element method, renewable energy, risk assessment and mitigation strategies, solar panel, structural load, wind loads

1. Introduction

The growing global need for sustainable energy sources has resulted in the extensive utilization of solar panels on a global scale (Obaideen et al., 2023). Solar panels are specifically engineered to transform sunlight into electrical energy and are frequently employed in expansive solar installations (Turney and Fthenakis, 2011). The structural components of solar panels are essential for maintaining the stability and dependability of these devices (Ramayanti and Budiantoro, 2021). Hence, it is imperative to conduct a comprehensive analysis of the effects of different wind loads on the structural robustness and longevity of the support systems for solar panels (Alanazi et al., 2020). There has been a significant rise in the utilisation of the Finite Element Technique (FEM) for analysing the structural integrity of support systems for solar panels (Mesnil et al., 2021). The FEM is a computational technique utilised for the resolution of engineering and mathematical physics issues by means of computer models (Liu et al., 2021). Mathew et al. (2013) demonstrated the utilisation of the FEM for the analysis of wind load effects on the structural integrity of solar panel supporting frames. The primary objective of this research is to assess the influence of different wind loads on the dependability and efficiency of the support structures for solar panels. This will be achieved by employing the FEM as outlined in the work of Wood et al. (2001). This study's primary goal is to determine how various wind loads affect the strength and sturdiness of the supporting frames for solar panels. The study's findings will yield important information for the development and improvement of the structural frameworks used in solar panel systems. The discovery holds significance due to its potential to enhance the design and optimisation of supporting structures for solar panels (Razzaque et al., 2023). It is anticipated that there will be a rise in the utilisation of renewable energy sources in the coming years, with a corresponding increase in the prevalence of large-scale solar arrays (Syranidou et al., 2020). Therefore, in order to guarantee the best possible performance from solar panels, it is essential to analyze the effects of wind loads upon the foundational strength and the effectiveness of support structures.

*Corresponding author. Tel.: 91-9952137381.
E-mail address: magnaparthi@gmail.com (J. Parthipan).

ISSN: 2663-6859 print/2663-6867 online
 doi:10.3808/jeil.202400136

2. Literature Review

In recent years, there has been an increasing prevalence of FEM utilisation in the examination of supporting structures for solar panels (Choi et al., 2022). Many researchers have used the FEM to analyze in great detail how wind loads affect the strength and structural integrity of the structures that support solar panels. Using ANSYS Workbench as the analysis tool, Wang et al. (2021) investigated how wind loads affected the structural behavior of supporting structures for solar panels. The findings of the study revealed a positive correlation between wind loads and both equivalent stress and total deformation, indicating that as wind loads grew, so did the levels of equivalent stress and total deformation. Chen et al. (2021) conducted a study to examine the aerodynamic characteristics of solar panels subjected to varying wind loads through the utilization of computational fluid dynamics (CFD) techniques. The experiment yielded results that demonstrated a positive association between wind speeds and the magnitudes of drag and lift forces experienced by the solar panels. The research findings also demonstrated a negative association between wind speeds and the lift coefficient of the solar panels. A study by Peng et al. (2023) explored at how wind loads and self-weight affected the structural integrity of buildings that house solar panels. The present study was conducted utilizing the FEM. The study's results demonstrated a significant positive association between wind loads and both maximum stress and total deformation. This suggests that an increase in wind loads corresponds to an increase in stress levels and deformation. Furthermore, the analysis unveiled that the areas experiencing the greatest levels of stress were primarily localized at the intersections of the underlying structural structure. Several researchers have also undertaken studies on the impact of wind loads on the effectiveness of solar panels. In their work, Polcovnicu et al. (2022) conducted an investigation into the impact of wind loads on the electrical efficiency of solar panels. This was achieved by the utilization of FEM analysis. The findings of the study indicate a negative correlation between wind speeds and the output power of the solar panels. In a separate investigation conducted by Yang et al. (2021), the examination of wind loads on the thermal efficiency of solar panels was undertaken using the utilization of FEM. The findings of the investigation indicated a positive correlation between wind speeds and the temperature of the solar panels. In recent years, there has been a growing trend in the adoption of solar panels, mostly driven by their cost-effectiveness and environmentally sustainable attributes. Nevertheless, the structural reliability of these elements may be compromised due to their exposure to wind stresses, therefore necessitating a comprehensive examination of their performance across various wind scenarios. This review of the literature focuses on recent studies that investigate how wind affects the structural stability of solar panel mounting systems. A study by Morad et al. (2018) studied how wind speed affected a rooftop solar panel mounting system's structural integrity. The researchers employed finite element analysis to evaluate the response of the system under varying wind velocities. Their findings indicate a shift in the system's failure mode as wind speeds escalate, accompanied by a corresponding increase in the likelihood of system failure. The study conducted by Al-rawashdeh and Stathopoulous (2022) employed numerical simulations to examine the efficacy of tuned mass dampers in mitigating wind-induced vibrations in solar panel mounting systems. Their research findings indicate that the implementation of tuned mass dampers is an efficient strategy for mitigating vibrations in the system, enhanceing its structural stability when subjected to wind loads. Su et al. (2018) conducted a study that examined the application of magnetorheological dampers for the purpose of mitigating wind-induced vibrations in structures supporting solar panels. In addition, the researchers discovered that the implementation of dampers resulted in a decrease in the vibrations of the system, suggesting that dampers possess considerable potential as a means of enhancing the structural integrity of solar panel systems. The study undertaken by Wang et al. (2021) involved numerical research into the phenomenon of wind-induced vibrations in utility-scale solar panel systems. The research conducted by the authors emphasized the significance of incorporating the wind pressure distribution into the evaluation of the structural integrity of solar panel systems. In Zhang et al. (2020) study, an experimental inquiry was done to see how a photovoltaic system responded to wind-induced conditions. The researchers observed a positive correlation between wind speeds and the amplitude of vibrations in the system. Additionally, they noted that the system's response was influenced by the characteristics of its support structure. The study conducted by Leitch et al. (2016) examined the impact of wind pressure distribution on the structural integrity of a solar farm. The study emphasized the significance of incorporating wind pressure distribution into the design of solar panel systems, as different wind directions can result in varying degrees of system damage. In a study conducted by Yao et al. (2022), an investigation was undertaken to examine the aerodynamic properties of a solar panel system situated in a coastal region. The study underscored the significance of incorporating wind direction and turbulence severity into the design of solar panel systems in coastal regions. In their study, Yemenici (2021) conducted an investigation on the impact of wind speed on the operational efficiency of a fixed-tilt solar module. The study conducted by the researchers revealed a negative correlation between wind speeds and the power production of the module, suggesting the necessity of accounting for the impact of wind on the performance of solar panels. In summary, the research examined in this literature review underscore the significance of taking into account the impact of wind on the structural dependability and efficacy of solar panel systems. The implementation of dampers and the incorporation of wind pressure distribution analysis are viable approaches for enhancing the structural integrity of solar panel systems across varying wind scenarios. The literature evaluation is essential to the research study's foundational framework and will guide the techniques employed to examine how wind loads affect the integrity of the structure of solar panel support systems in the current study.

3. Materials and Methods

The study is limited in scope to the investigation of the structural response of a conventional solar panel support system under varying wind loads. The primary aim of this research is to provide a thorough comprehension of the impacts of wind loads on the structural integrity of support systems for solar panels. The motivation behind doing this study arises from the growing adoption of renewable energy sources, particularly solar electricity. The assurance of the dependability and effectiveness of the supportive frameworks for solar panels is of paramount significance, given the growing importance of large-scale solar arrays. The primary aim of this research is to evaluate the influence of different wind loads on the structural soundness and robustness of the support frameworks for photovoltaic panels through the utilization of FEM analysis. ANSYS Workbench software was used as the research approach in this work to examine how wind loads affect the integrity of the structure and durability of solar panel support structures. The ANSYS Workbench programme, known for its strong capabilities in structural and fluid dynamics analysis (Agarwal et al., 2021), was utilised for the simulation. The following formulas and general equations were used in this study (Waqas et al., 2020).

Airflow pressure and velocity:

$$P = 0.5 \times \rho \times V^2 \quad (1)$$

where $V = Q / A$, "P" stands for air flow pressure, "ρ" for air density, "V" for wind velocity, "Q" for volumetric flow rate, and "A" for the structure's cross-sectional area.

Lift coefficient:

$$CL = L / (0.5 \times \rho \times V^2 \times A) \quad (2)$$

where CL is the lift coefficient, L is the lift force, and A is the cross-sectional area of the structure.

Total deformation:

$$\Delta = (FL^3) / (3EI) \quad (3)$$

where the variables denoted by Δ, F, L, E, and I are the total deformation, force applied, modulus of elasticity, and moment of inertia, respectively.

Maximum equivalent stress:

$$\sigma = (M / Z) + (F / A) \quad (4)$$

where Z is the section modulus, F is the applied force, A is the structure's cross-sectional area, σ is the equivalent stress, and M is the bending moment.

The methodology utilised in this research will be organised in a systematic manner, following a series of consecutive steps: The selection of the research design utilised in this study plays a pivotal role in determining the overall credibility and dependability of the results. The present investigation employs a numerical simulation research design to scrutinize the structural dependability and robustness of support structures for solar panels under diverse wind loads. The study examined the effects of varying wind speeds on the structural strength of the solar panel mounting system using the FEM. The subject of discourse pertains to the field of geometry modelling. The first step in the analysis consisted of creating the geometric model of the supporting framework for the solar panel using ANSYS Workbench software. The model was constructed by using the design ideas commonly employed in a traditional solar panel support structure (illustrated in Figure 1), while strictly conforming to the dimensional criteria set forth by industry norms.

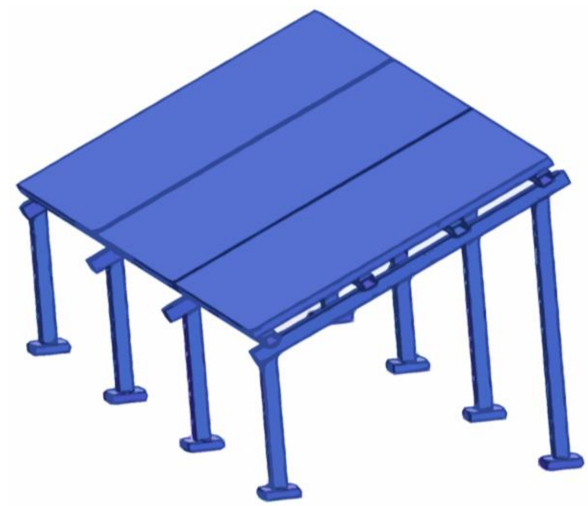

Figure 1. 3D Model of solar panel supporting structure.

Different sub-technologies of solar panels, such as crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), may exhibit varying responses to wind loads due to differences in their material properties, structural designs, and installation methods. The impact of wind loads on each type of solar panel technology could differ based on factors such as flexibility, weight, and overall structural robustness (Paranthaman and Azam, 2023). Further research focusing on the specific effects of wind loads on different sub-technologies of solar panels could provide valuable insights for optimizing support structures and enhancing the durability and performance of solar energy systems.

Mesh Generation: Following the creation of the geometric model, the subsequent stage involved the generation of a mesh for the structural representation. The ANSYS Meshing tool was employed to generate the mesh, and the quantity of elements employed was established by the execution of a mesh sensitivity analysis. The model was discretized into 400,000 elements, a configuration that struck a favourable compromise between precision and computational expenditure are presented in Figure 2. Prior to doing the analysis, the quality of the mesh was assessed and any identified faults were rectified.

The loading condition of the structure was also considered in relation to its own weight. Boundary conditions were applied to the lower section of the supporting structure to limit its horizontal displacement. Additionally, steps were used to ensure the stability of the upper section of the construction, aiming to minimise any possible vertical movement. The primary objective of this discourse is to examine a range of analysis approaches that are frequently utilised in academic research.

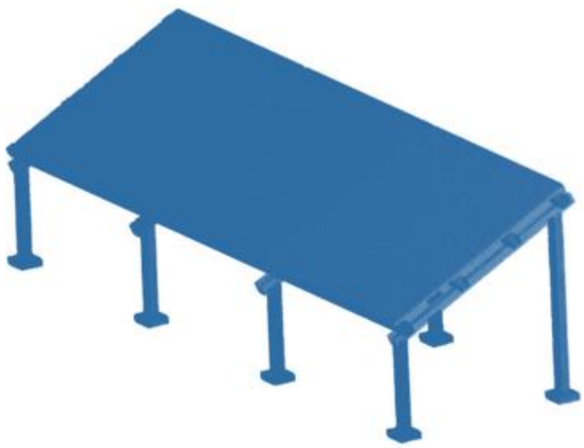

Figure 2. Meshing of the framework that supports solar panels.

The utilisation of the FEM was employed to carry out a comprehensive analysis on the structural reaction of the supporting structure designed for solar panels. The analysis was performed utilising the ANSYS Mechanical software, resulting in findings pertaining to overall deformation and the highest magnitude of equivalent stresses. The maximum equivalent stress and overall deformation were calculated and afterward compared among various wind velocities.

The results obtained from the FEM analysis were subsequently utilised to evaluate the structural integrity of the supporting framework for the solar panel. The structural integrity of the solar panel support system was affected by the wind-induced drag and lift forces exerted against it. The deformation of the supporting structure can be attributed to the aerodynamic forces, specifically the air flow pressure and velocity, acting upon the surfaces of the solar panels. The regions exhibiting the highest equivalent stress were determined to be the joint sections of the supporting framework for the solar panel. The significance of this discovery cannot be overstated, as it has direct implications for the stability and structural integrity of the system. The deformation of the structure was seen to have larger magnitudes in both the central region and the base. This indicates a potential danger of structural instability and consequent failure.

4. Results and Discussion

The results revealed that the aerodynamic properties of the support structure for the solar panel were impacted by both the lift coefficient and the structural self-weight. As the wind speed increased, there was a concomitant elevation in the lift coefficient, resulting in an amplification of the drag force applied to the supporting structure of the solar panel (represented in Figure 3). The self-weight of the solar panel supporting structure has a substantial impact on its structural integrity.

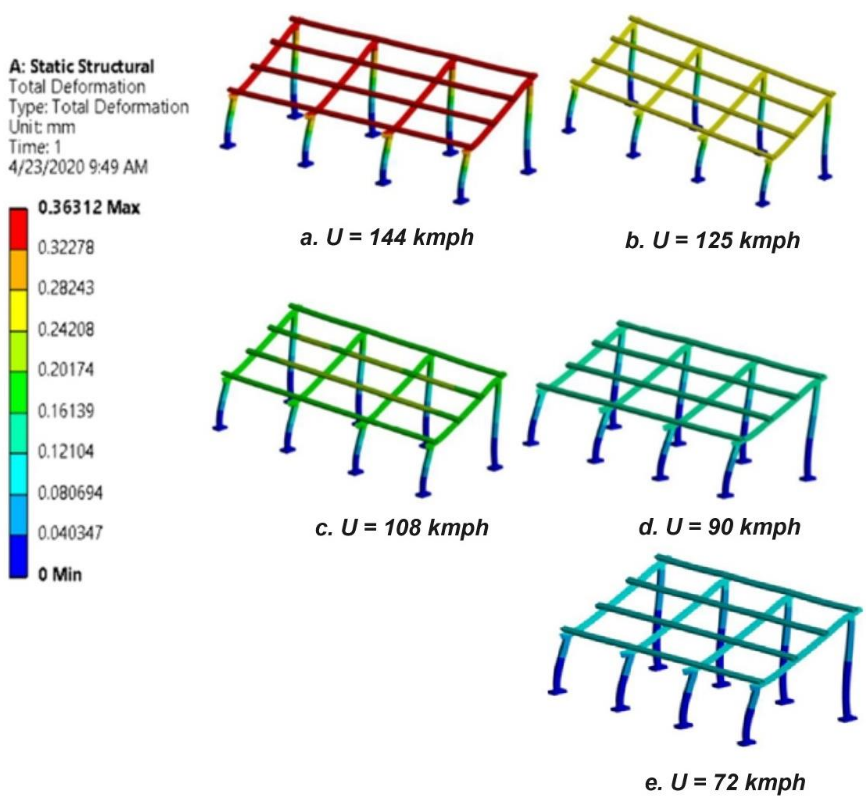

Figure 3. Total deformation at various wind loads.

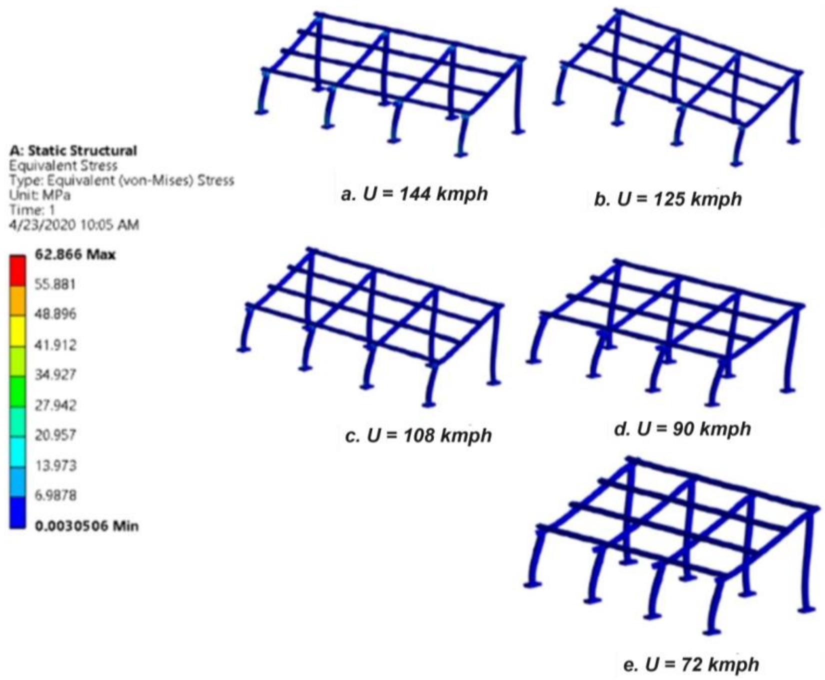

Figure 4. Von Mises stress at various wind loads.

The subsequent Table 1 illustrates the relationship between wind load and total deformation, as well as wind load and maximum equivalent stress. The results suggest that there is a direct relationship between wind speed and the levels of total deformation and maximal equivalent stress. The highest overall deformation of 0.3631 mm was seen when the wind velocity reached 144 kmph, while the lowest overall deformation of 0.0895 mm was recorded at a wind velocity of 72 kmph. The highest documented maximum equivalent stress was obtained at a wind velocity of 144 kmph, exhibiting a magnitude of 62.87 MPa. In contrast, the minimum recorded value of 16.08 MPa was reported when the wind speed reached 72 kmph. The aforementioned findings are of importance within the context of designing supportive structures for solar panels, as they enhance the capacity to withstand various wind loads and uphold the structural integrity and stability of the solar panel system (represented in Figure 4). The following table provides a comparative analysis of the results obtained from the current research study and previous investigations about the analysis of wind effects on structures that support solar panels.

Table 1. Wind Load Effects on Solar Panel Supporting Structure

Wind Speed (kmph)	Total Deformation (mm)	Max Equivalent Stress (Mpa)
72	0.0895	16.08
90	0.1196	20.50
108	0.1812	31.20
125	0.2525	46.75
144	0.3631	62.87

The findings of the present study align with prior research, which has demonstrated that wind loads exert a substantial influence on the structural soundness of support systems for solar panels. However, it is important to acknowledge that the maximum and minimum values of equivalent stress and total deformation were observed at different wind velocities (shown in Table 2).

The observed mismatch underscores the need for further work to improve the design of support systems for solar panels. The findings indicate that it is crucial to construct the supportive framework of solar panels to withstand high wind velocities in order to ensure their stability and reliability. Considering the aerodynamic properties of the structure and the forces of drag and lift acting on it is crucial.

Furthermore, a comprehensive understanding of stress distribution and deformation is crucial in the context of structural design, since it directly influences the stability and strength of the given structure. The results of this study provide valuable insights into the effects of wind loads on the structural stability of support systems for solar panels. These findings contribute to the existing knowledge and aid in the design of efficient structures for large-scale solar arrays.

Risk Assessment: The study identifies several key risks associated with higher wind speeds impacting the stability and robustness of solar panel support structures. Excessive wind speeds can result in significant deformation of support structures, potentially leading to failure modes such as buckling, fracture, or detachment of panels. Joints and connections within the support structures are particularly vulnerable to higher stresses, with failure at these points posing a risk of collapse for entire arrays. Additionally, foundation failure is a concern if wind uplift forces surpass the holding capacity of piles or anchors, potentially causing tipping or detachment of support structures. Coastal or cyclone-prone areas face heightened risks due to the potential

Table 2. Comparison Studies on the Wind Analysis of Solar Panel Supporting Structures

Study	Methodology	Results
Current study	Finite element method (FEM)	Wind loads have a considerable impact on the structural integrity of solar panels. The maximum and minimum values of equivalent stress and total deformation were determined for velocities of 144 and 72 kmph, respectively.
Khan et al. (2023)	Computational fluid dynamics (CFD)	The central region of the solar panel support structure displayed the highest magnitude of equivalent stress, but the corners of the structure demonstrated more overall deformation.
Lang et al. (2022)	Finite element method (FEM)	The structural response of the supporting structures for solar panels was significantly influenced by wind loads, leading to the corners of the structure experiencing the most pronounced degrees of displacement and stress.
Liang et al. (2020)	Mechanical Analsysis and ABACUS	The research work investigates the mechanical analysis of photovoltaic panels under various boundary conditions, which may include factors such as temperature variations, mechanical loading, and structural constraints of the panels themselves. Their study likely delves into the effects of these boundary conditions on the performance and durability of photovoltaic panels.

for very high winds exceeding design limits, which could result in prolonged shutdowns of power production. Furthermore, vibrations induced at resonant wind speeds may lead to fatigue failures over time, even if stresses initially remain below yield levels.

Mitigation Strategies: To address these risks, it is recommended to reinforce critical joints, connections, and central load-bearing members to withstand higher stresses by utilizing bracing, gusset plates, and stronger materials. Strengthening foundations through increased pile embedment depth or additional guys/anchors can help counteract higher uplift forces. The installation of tuned mass dampers, magnetorheological dampers, or other vibration control devices is advised to absorb resonant vibrations and prevent fatigue failures. Consideration should be given to using distributed or balanced structural designs that experience more uniform stresses, rather than designs with single load paths. Incorporating real wind data specific to the site location in the design process, beyond code-specified basic wind speeds, is crucial to account for potential storms. Conducting fatigue analysis over the expected lifespan and scheduling preventive maintenance and inspections are essential steps to ensure long-term structural integrity. Implementing remote monitoring systems capable of detecting structural damage early through performance and vibration parameters is recommended to enhance overall safety and reliability.

Recommendations: Stakeholders are encouraged to evaluate identified risks based on location and design specifics and implement appropriate mitigation strategies to strengthen critical components, foundations, and control vibrations. An integrated approach encompassing structural design, material selection, and monitoring practices can enhance resilience against wind loads and reduce the likelihood of power outages. Regular periodic inspection and maintenance procedures are vital to ensure the ongoing safety and performance of solar panel support structures.

5. Conclusions

This study utilized the finite element method to investigate the effects of various wind load on the structural integrity and strength of support structures for solar panels. By analyzing different wind speeds ranging from 72 to 144 kmph, the research highlighted the significant impact of wind stresses on the structural integrity of solar panels. The study identified areas of high equivalent stresses at joint portions of the support framework and observed notable deformation in the central region and foundation of the structure. Understanding stress distribution and deformation is crucial for effective design, stability, and performance of solar panel support structures. The maximum and minimum values of equivalent stress were measured as 62.87 and 16.08 MPa, respectively. In a similar manner, the measurements of total deformation yielded maximum and minimum values of 0.3631 and 0.0895 mm, respectively. The results offer insights that can enhance the reliability and efficiency of structural frameworks supporting solar panels, facilitating design optimization and performance enhancement through numerical modeling techniques like finite element methods.

Future Recommendations: While this study has advanced the understanding of supporting structures for solar panels, there are ample opportunities for further exploration in this field. Future research could focus on experimental validation to confirm hypotheses and theories. Conducting physical tests, such as wind tunnel experiments, can provide additional support for the conclusions drawn in this study, ensuring the accuracy and reliability of numerical simulations. Design optimization strategies like topology, form, and size optimization can enhance the functionality of support structures for solar panels. Further investigations into material choices and their impact on structural reliability and strength can optimize support structures. Analyzing environmental factors such as temperature and humidity on the structural soundness of support systems for solar panels can also be a valuable area of inquiry. Overall, this study underscores the significant impact of wind loads on the structural reliability of solar panel support frameworks and emphasizes the importance of understanding stress distribution and deformation for designing stable and structurally sound support systems in the renewable energy sector. Future research in this field has the potential to advance the design and performance of support structures for solar panels, contributing to the progress of renewable energy systems.

Acknowledgements. The authors are grateful to IMD and India WRIS for providing the required data for analysis.

References

Agarwal, A., Irtaza, H. and Ahmad, M.J. (2021). Numerical analysis of the ground-mounted solar PV panel array mounting systems subjected to basic wind for optimum design. *Canadian Journal of Civil Engineering*, 48(6), 656-668. https://doi.org/10.1139/CJCE-2019-0280

Alanazi, M., Mahoor, M. and Khodaei, A. (2020). Co-optimization generation and transmission planning for maximizing large-scale solar PV integration. *International Journal of Electrical Power and Energy Systems*, 118, 105723. https://doi.org/10.1016/j.ijepes.2019.105723

Alrawashdeh, H. and Stathopoulos, T. (2022). Experimental investigation of the wind loading on solar panels: Effects of clearance off flat roofs. *Journal of Structural Engineering*, 148(12). https://doi.org/04022202. 10.1061/jsendh/steng-10957

Chen, Y. and Wang, J. (2021). Design optimization and numerical analysis of wind load for large water surface photovoltaic power station. *Journal of Guangdong University of Petrochemical Technology*, 31(6), 33-35,39. https://doi. org/10.3969/j.issn.2095-2562.2021.06.009

Choi, S.M., Park, C.D., Cho, S.H. and Lim, B.J. (2022). Effects of wind loads on the solar panel array of a floating photovoltaic system – Experimental study and economic analysis. *Energy*, 256, 124649. https://doi.org/10.1016/j.energy.2022.124649

Khan, A.K., Shah, T.R., Khosa, A.A. and Ali, H.M. (2023). Evaluation of wind load effects on solar panel support frame: A numerical study. *Engineering Analysis with Boundary Elements*, 153, 88-101. https://doi.org/10.1016/j.enganabound.2023.05.016

Lang, M., Oreski, G., Helfer, E., Halm, A., Klenk, M. and Fuchs, P. (2022). FEM simulation of deformations and stresses in strings of shingled solar cells under mechanical and thermal loading. *AIP Conference Proceedings*, 2709(1), 020008.

Leitch, C.J., Ginger, J.D. and Holmes, J.D. (2016). Wind loads on solar panels mounted parallel to pitched roofs, and acting on the underlying roof. *Wind and Structures*, 22(3), 307-28. https://doi.org/10.12989/WAS.2016.22.3.307

Liang, X., Deng, Y., Jiang, X., Cao, Z., Ruan, Y., Leng, J., Wang, T. and Zha, X. (2020). Three-dimensional semi-analytical solutions for the transient response of functionally graded material cylindrical panels with various boundary conditions. *Journal of Low Frequency Noise*, Vibration and Active Control, 39(4), 1002-1023. https://doi.org/10.1177/1461348419855807

Liu, H.D., Zhang, P., Lai, Z.Q., Dong, X.F., Wang, Z.C. and Zhou, S.M. (2021). Fluid structure interaction-based structure stress and modal analysis of a flat type solar panel supporting system. *E3S Web of Conferences*, Hangzhou, 248, 1-6.

Mathew, A., Biju, B., Mathews, N. and Pathapadu, V. (2013). Design and stability analysis of solar panel supporting structure subjected to wind force. *International Journal of Engineering Research and Technology*, 2(12). 559-565. https://doi.org/10.17577/ijertv2is120210

Mesnil, O., Recoquillay, A., Druet, T., Serey, V., Hoang, H.T., Imperiale, A. and Demaldent, E. (2021). Experimental validation of transient spectral finite element simulation tools dedicated to guided wave-based structural health monitoring. *Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems*, 4(4), 041003. https://doi.org/10.1115/1.4050708

Morad, A.M.A., Al-Sayyab, A.K.S. and Abdulwahid, M.A. (2018). Optimisation of tilted angles of a photovoltaic cell to determine the maximum generated electric power: A case study of some Iraqi cities. *Case Studies in Thermal Engineering*, 12, 484-488. https://doi.org/10.1016/j.csite.2018.07.001

Obaideen, K., Olabi, A.G., Al Swailmeen, Y., Shehata, N., Abdelkareem, M.A., Alami, A.H., Rodríguez, C. and Sayed, E.T. (2023). Solar energy: Applications, trends analysis, bibliometric analysis and research contribution to Sustainable Development Goals (SDGs). *Sustainability*, 15(2), 1418. https://doi.org/10.3390/ su15021418

Paranthaman, R. and Azam, S. (2023). Parametric design and field behavior of earthen structures. *Journal of Environmental Informatics Letters*, 9(2), 60-69. https://doi.org/10.3808/jeil.202300102

Peng, H.Y., Dai, S.F. and Liu, H.J. (2023). Wind loading characteristics and roof zoning of solar arrays mounted on flat-roofed tall buildings. *Journal of Building Engineering*, 66, 105823. https://doi.org/10.1016/j.jobe.2023.105823

Polcovnicu, R. A., Taranu, N., Ungureanu, D. and Hudisteanu, S.V. (2022). Wind load evaluation of roof photovoltaic panels loaded in the boundary layer wind tunnel. *International Journal of Modern Manufacturing Technologies*, XIV(3), 205-210 https://doi.org/10.5684/ijmmt.2022.14.3.205

Ramayanti, S. and Budiantoro, P. (2021). Design analysis of solar panel structure LAPAN-Constellation Satellite using finite element method. *IOP Conference Series: Materials Science and Engineering*, Padang, 1041(1). 012020.

Razzaque, A., Masmali, I., Hassan, R., Shuaib, U., Razaq, A., Alhamzi, G. and Noor, S. (2023). A modern strategy for the selection of efficacious solar panels at industrial level under an interval-valued picture fuzzy set hybrid environment. *Energies*, 16(14), https://doi.org/5338.10.3390/en16145338.

Su, K.C., Chung, K.M. and Hsu, S.T. (2018). Numerical simulation of wind loads on solar panels. *Modern Physics Letters B*, 32(12n13), 1840009. https://doi.org/10.1142/S0217984918400092

Syranidou, C., Linssen, J., Stolten, D. and Robinius, M. (2020). Integration of large-scale variable renewable energy sources into the future european power system: On the curtailment challenge. *Energies*, 13(20), 5490. https://doi.org/10.3390/EN13205490

Turney, D. and Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews*, 15(6), 3261-3270. https://doi.org/10.1016/j.rser.2011.04.023

Wang, C., Ma, W., Han, X. and Gao, F. (2021). Effect of parapet on wind load of flat roof array solar pannel. *Engineering Mechanics*, 38(S), 216-222. https://doi.org/10.6052/j.issn.1000-4750.2020.06.S039

Waqas, M., Khan, A., Ahmad, W., Rouf, A., Aslam, R. and Jamal, S. (2020). Numerical investigation of impact of various wind loads on the structural stability and strength of solar panel supporting structure. *North American Academic Research*, 3(05), 70-84. https://doi.org/10.5281/zenodo.3780500

Wood, G.S., Denoon, R.O. and Kwok, K.C.S. (2001). Wind loads on industrial solar panel arrays and supporting roof structure. *Wind and Structures*, 4(6). 481-494. https://doi.org/10.12989/was.2001.4.6.481

Yang, L., Yu, H. and Lin, L. (2021). Study on wind load calculation method of photovoltaic power array. *Energy and Environment*. 2021, 70-72. https://doi.org/10.3969/j.issn.1672-9064.2021.01.024

Yao, J., Tu, Z., Wang, D., Shen, G. and Lou, W. (2022). Experimental investigation of wind loads on roof-mounted solar arrays. *Sustainability*, 14(14), 8477. https://doi.org/10.3390/su14148477

Yemenici, O. (2021). Experimental evaluation of wind loads on a ground-mounted solar panel of various ground clearances and Reynolds numbers. *Sādhanā*, 46(4), 204. https://doi.org/10.1007/s12046-021-01718-w

Zhang, B., Song, B., Mao, Z., Tian, W. and Li, B. (2017). Numerical investigation on VIV energy harvesting of bluff bodies with different cross sections in tandem arrangement. *Energy*, 133, 723-736. https://doi.org/10.1016/j.energy.2017.05.051